Polarized thermal emission from Galactic dust as seen by Planck

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on behalf of the Planck Collaboration

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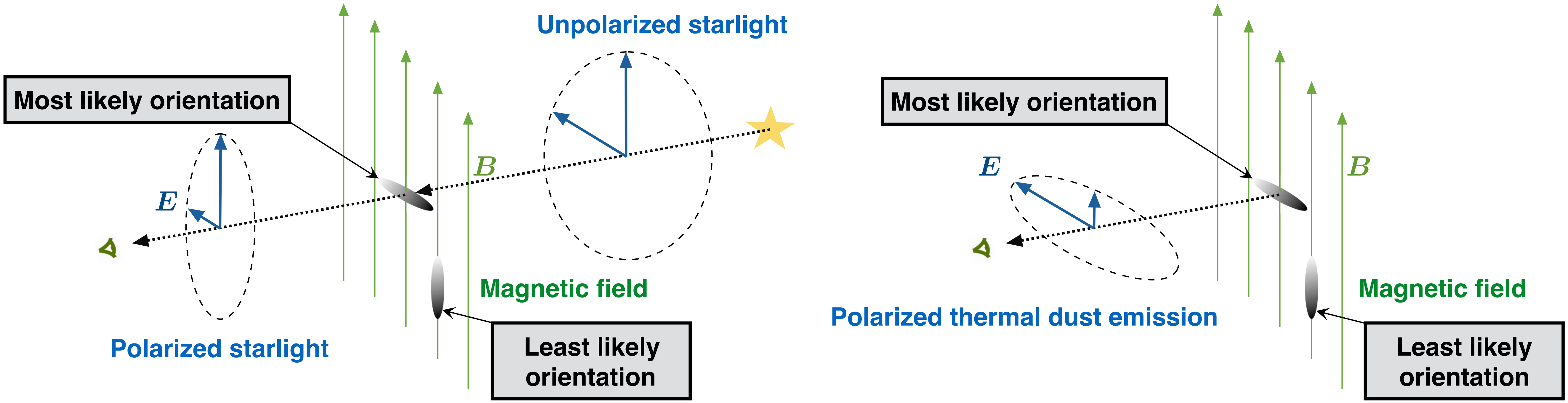
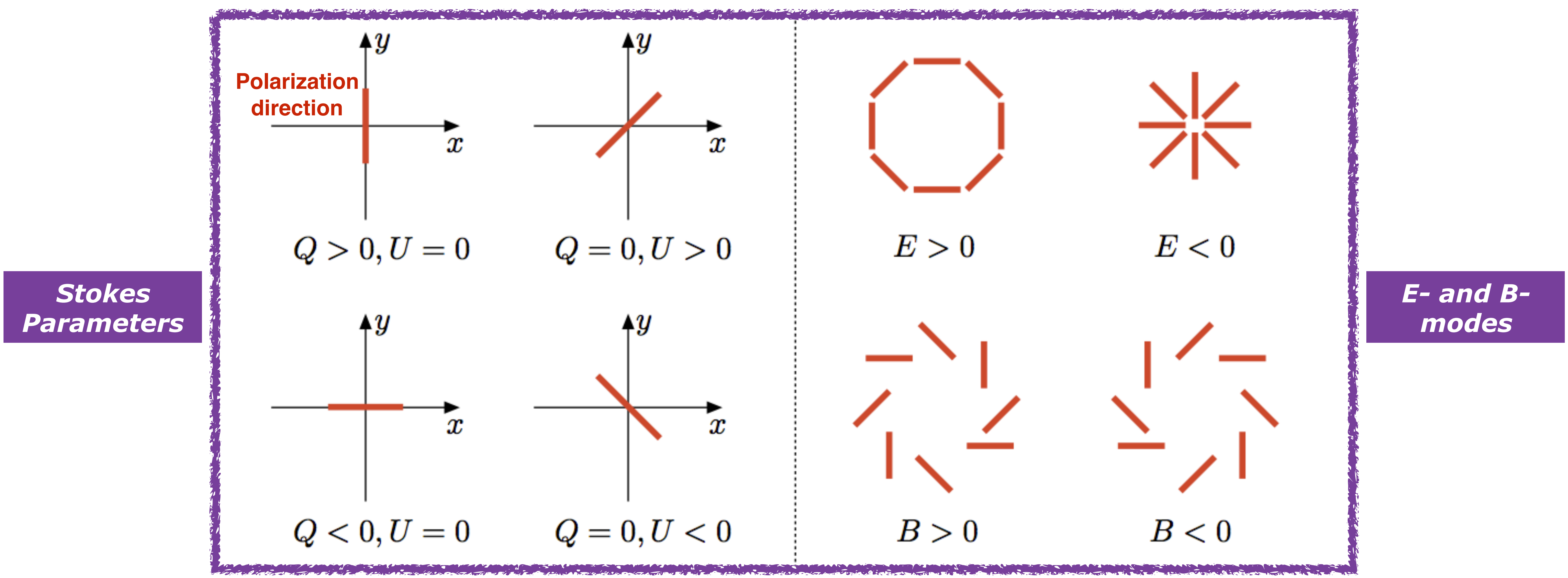
Dust, magnetic fields and polarization

- Aspherical, charged, rotating dust grains statistically align in the local magnetic field
- Background starlight emerges polarized parallel to the magnetic field
- Polarized thermal dust emission arises perpendicularly to the magnetic field



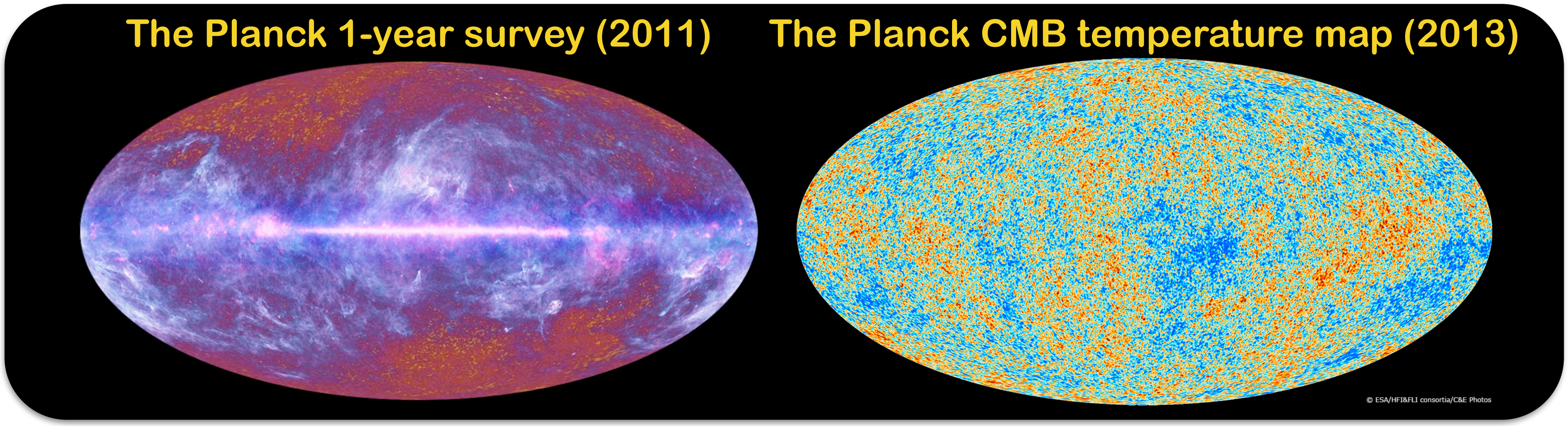


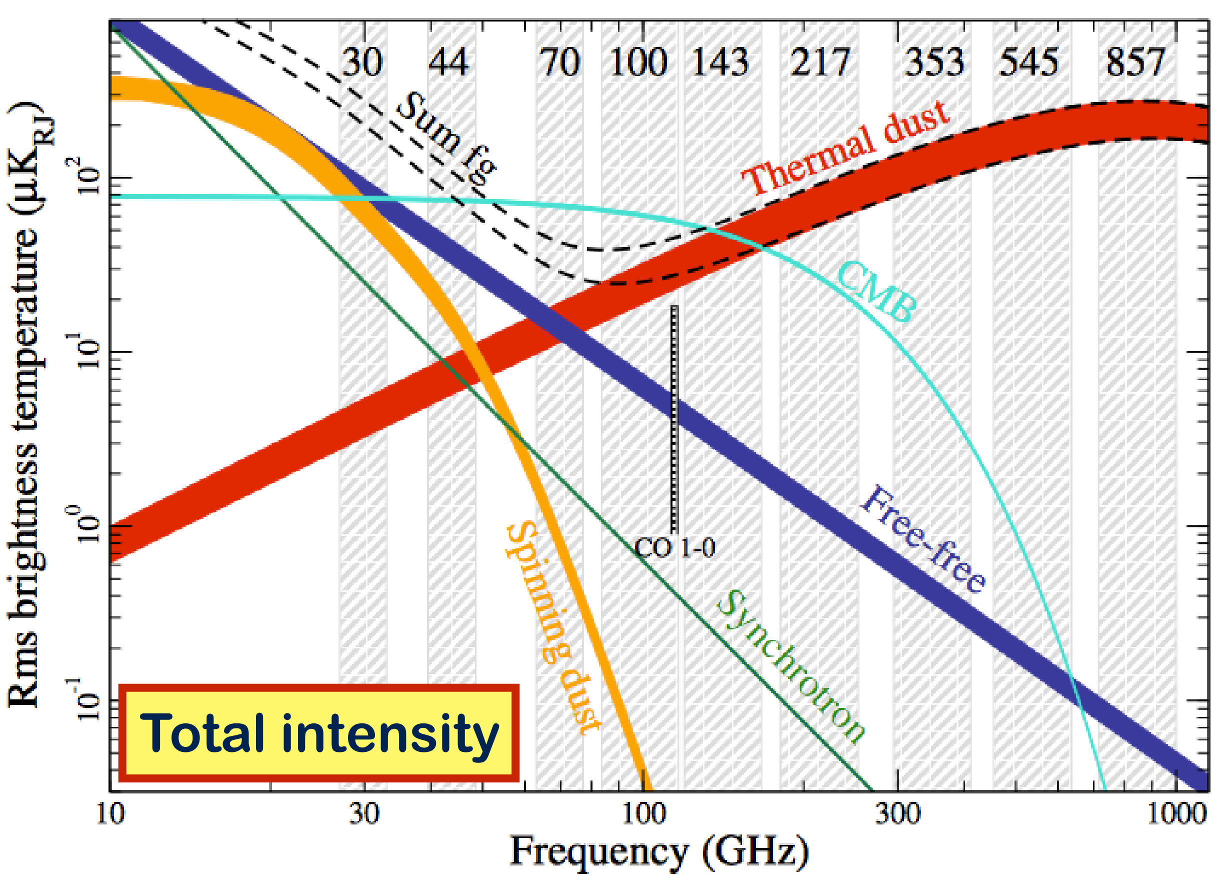
The Planck mission : CMB and foregrounds

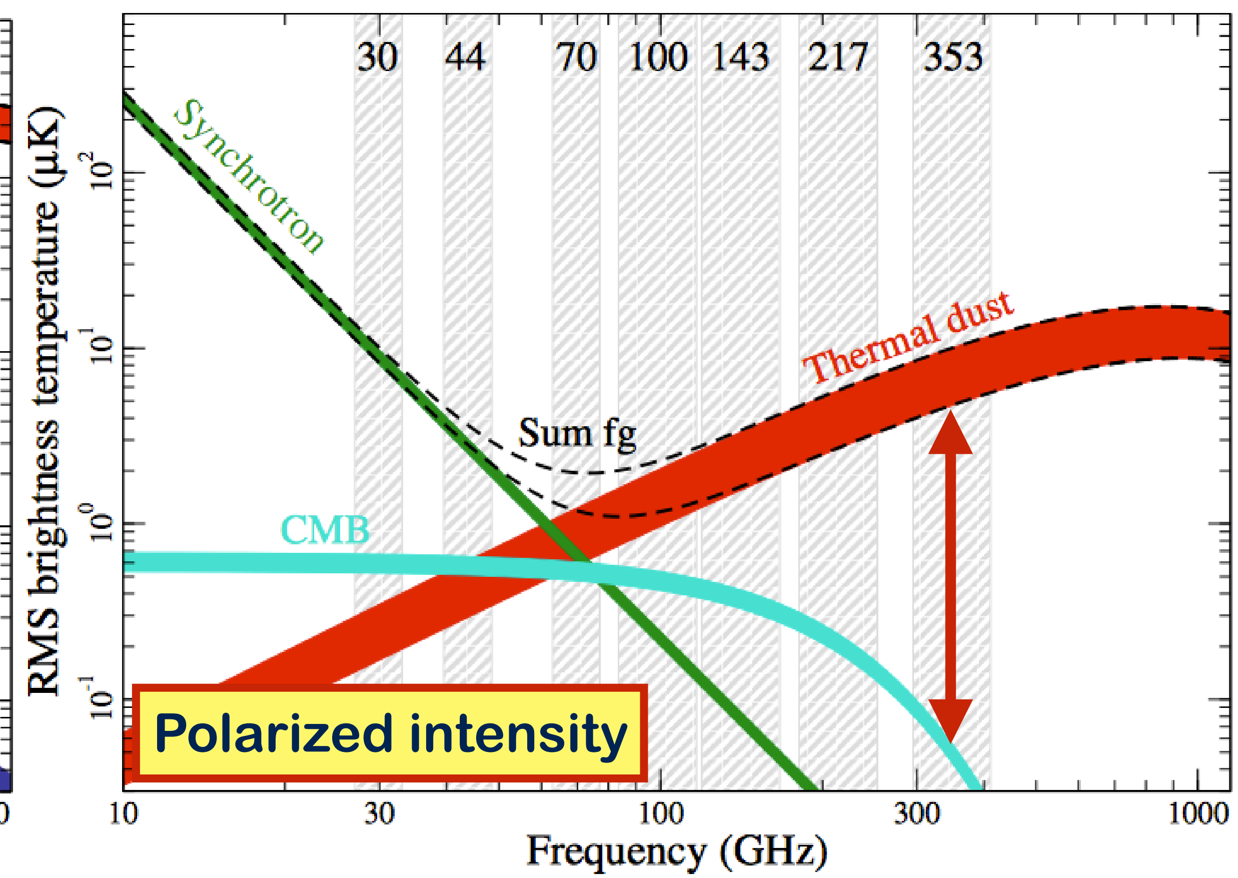
planck

- 2009-2013 European space mission : Full survey of the microwave sky
- 30 - 857 GHz coverage in nine bands
- Measurement of Cosmic Microwave Background (CMB) anisotropies
- Mapping of the cold, dusty Milky Way
- First full-sky survey in microwave polarization

Planck Collaboration I (2016)

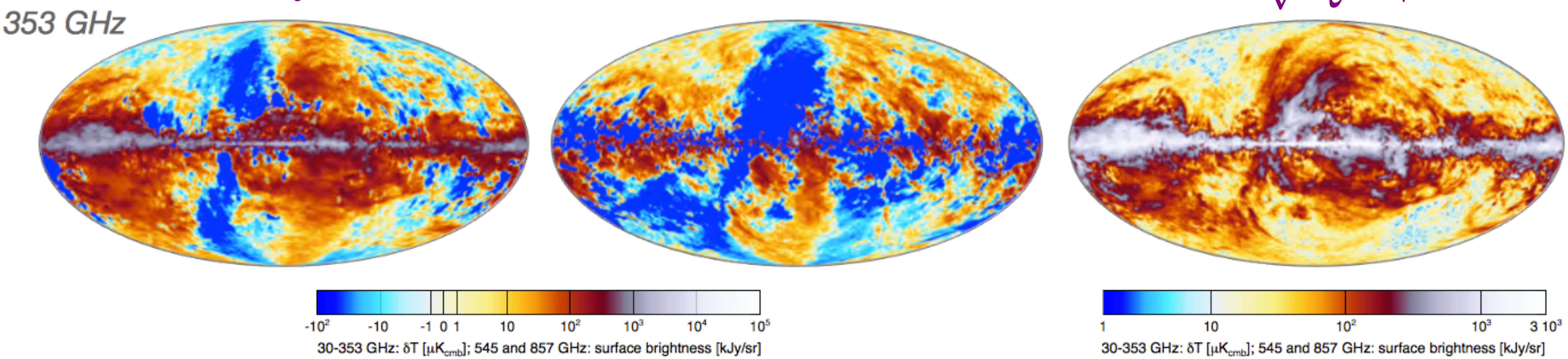




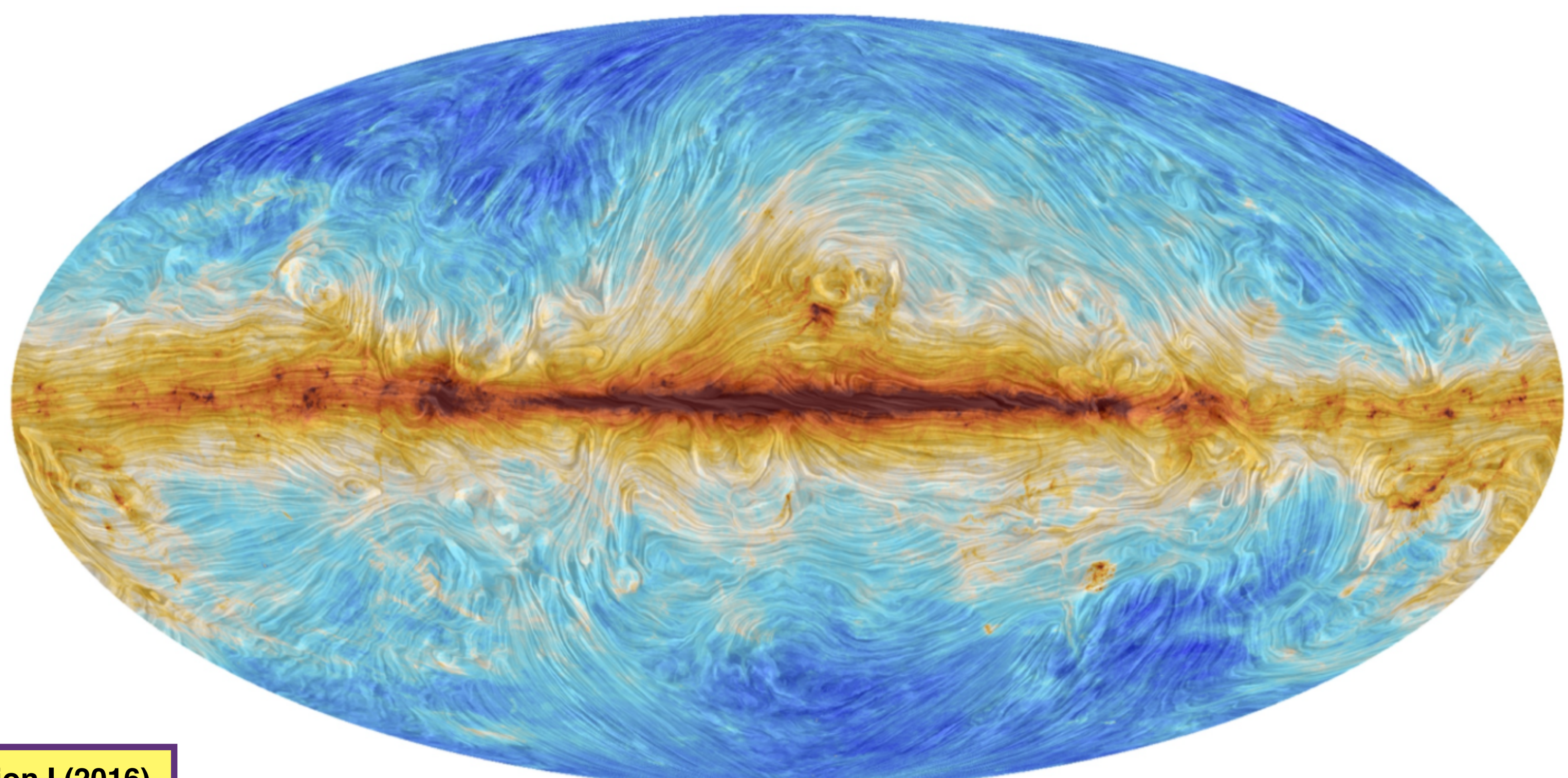


The Planck view of polarized thermal dust emission

Q $\qquad$ U $\qquad$ $P = \sqrt{Q^2 + U^2}$



Total intensity and « drapery » showing the « direction of the magnetic field »



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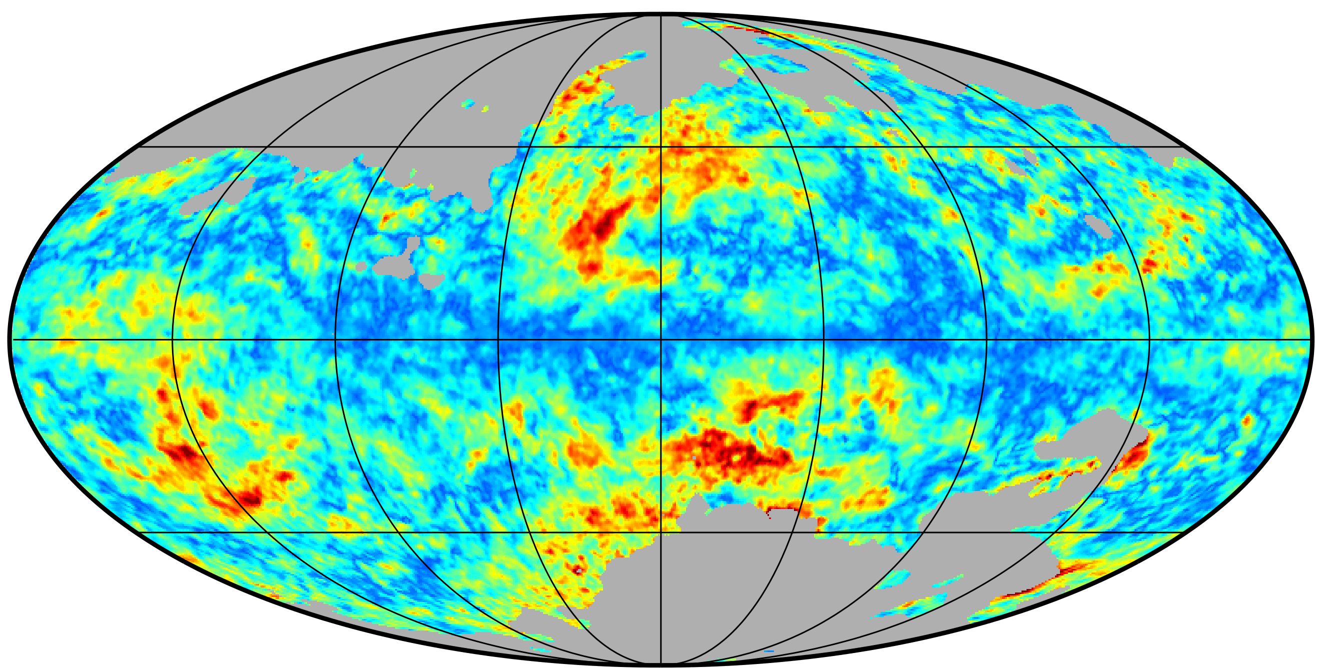
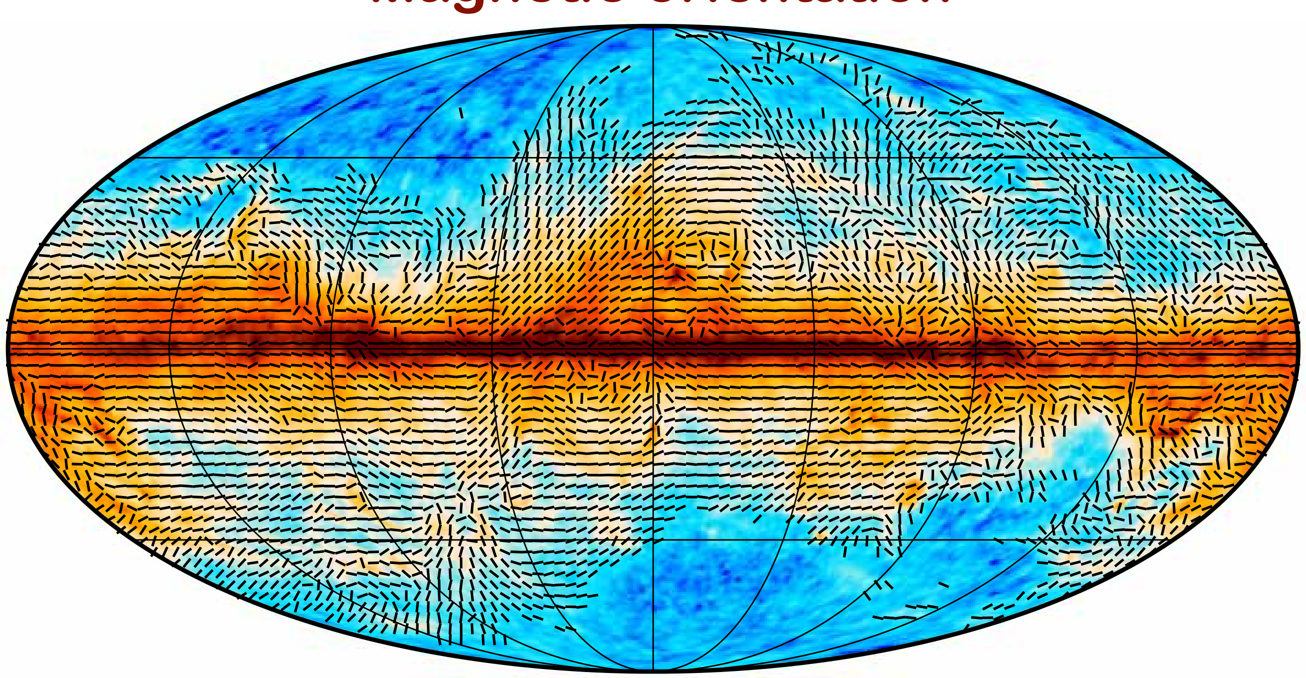
Properties of large-scale thermal dust polarization (2015)

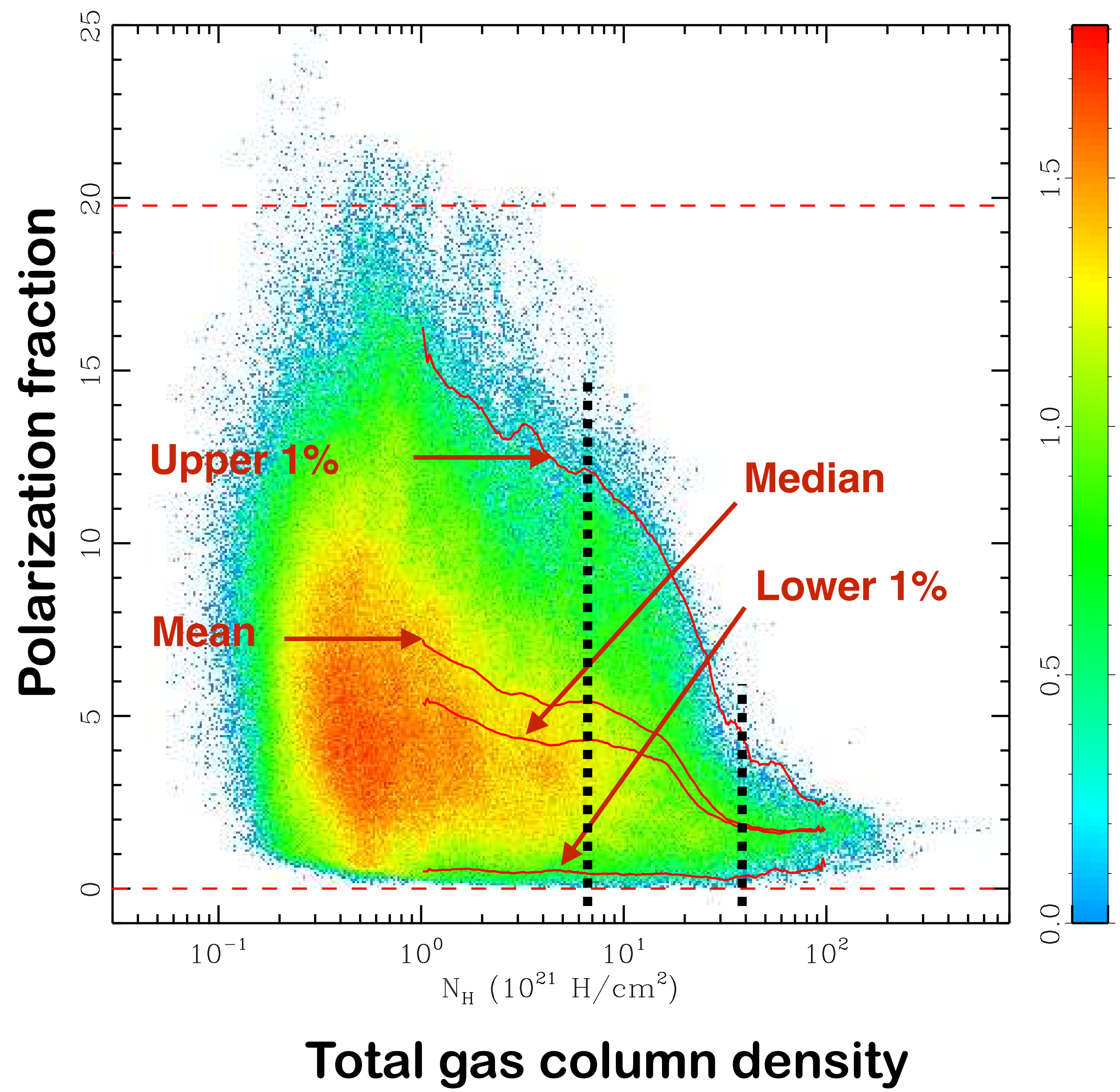
- Low polarization fractions in the Galactic Plane and some highly polarized regions
- Filamentary structures of low polarization with no material counterpart
- Large scatter of polarization fractions at low column densities
- Intrinsic dust polarization at least of order 20%
- Decrease of the maximum polarization fraction with increasing column density

Polarization fraction



Magnetic orientation





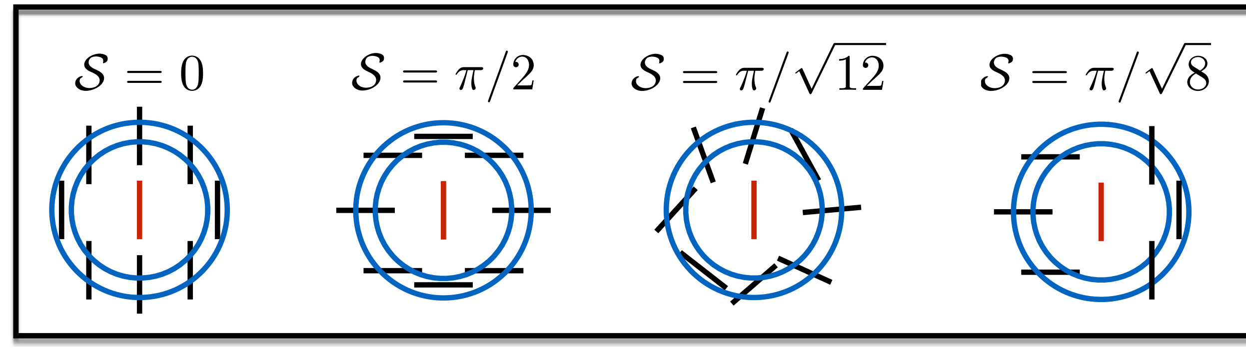
Planck Collaboration Int. XIX (2015)

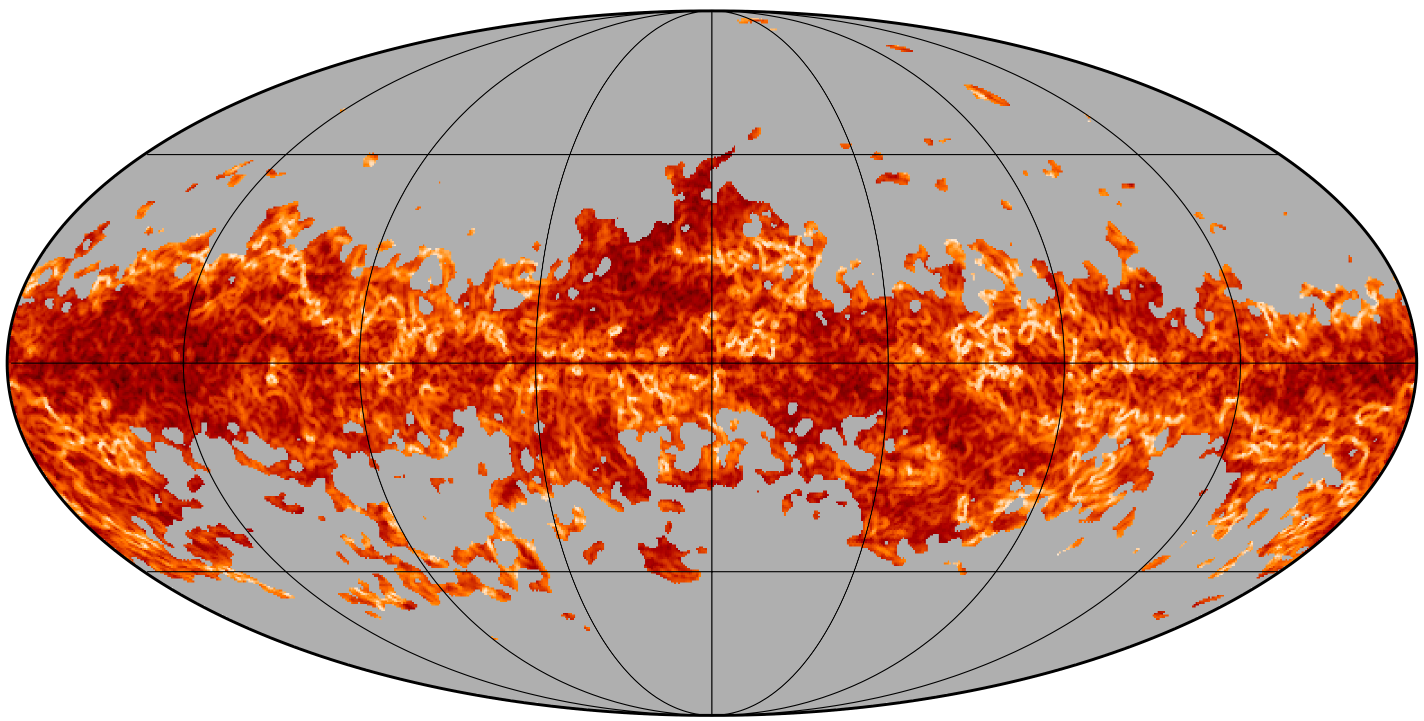
Update nearing completion

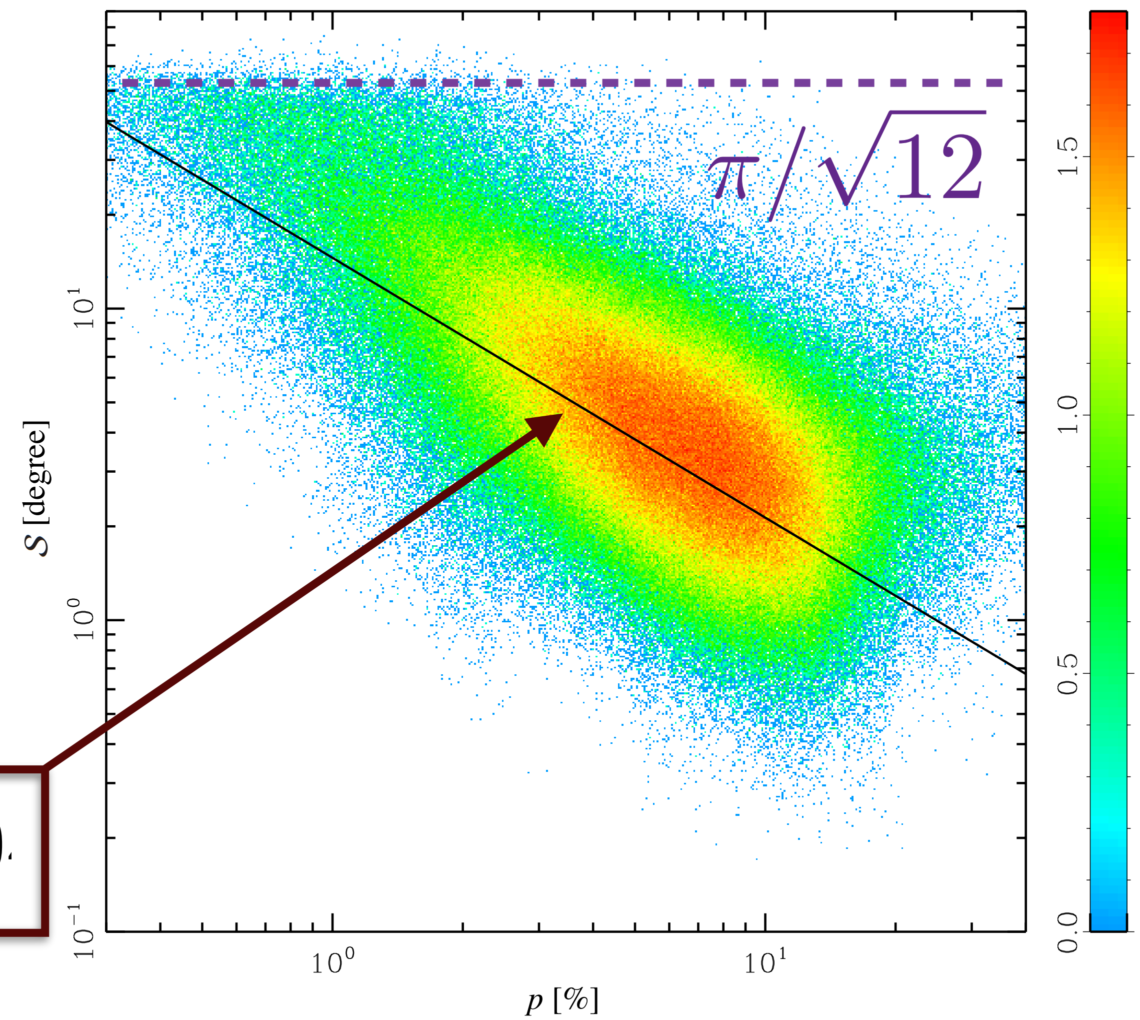
Spatial structure of the polarization angle map

Polarization angle dispersion function

$$\mathcal{S}(\boldsymbol{r},\delta) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\psi(\boldsymbol{r}+\boldsymbol{\delta}_i)-\psi(\boldsymbol{r})\right]^2}$$







$$\boxed{\log(\mathcal{S}/\,\mathrm{deg}) = -0.83\log p - 0.50}$$

- Strongly anti-correlated with the polarization fraction
- Low polarization fractions found where the polarization angle direction changes abruptly
- Increased lag δ flattens the anti-correlation

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Spatial structure of the polarization angle map

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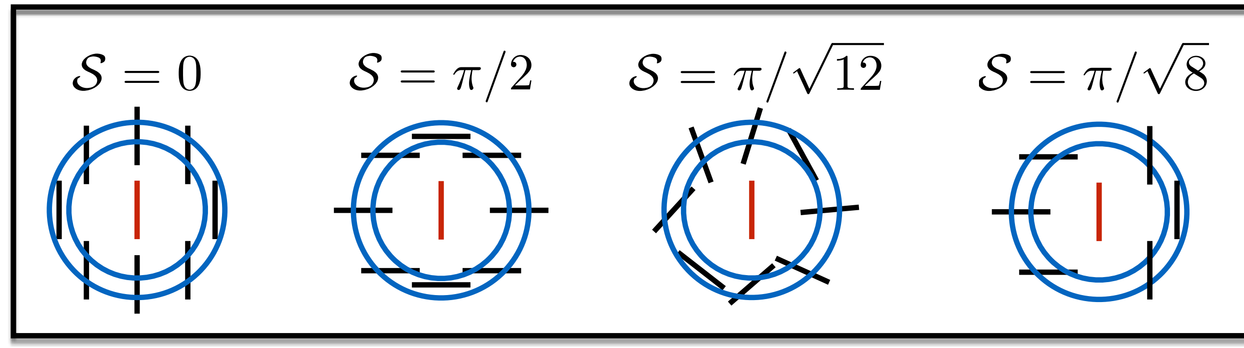

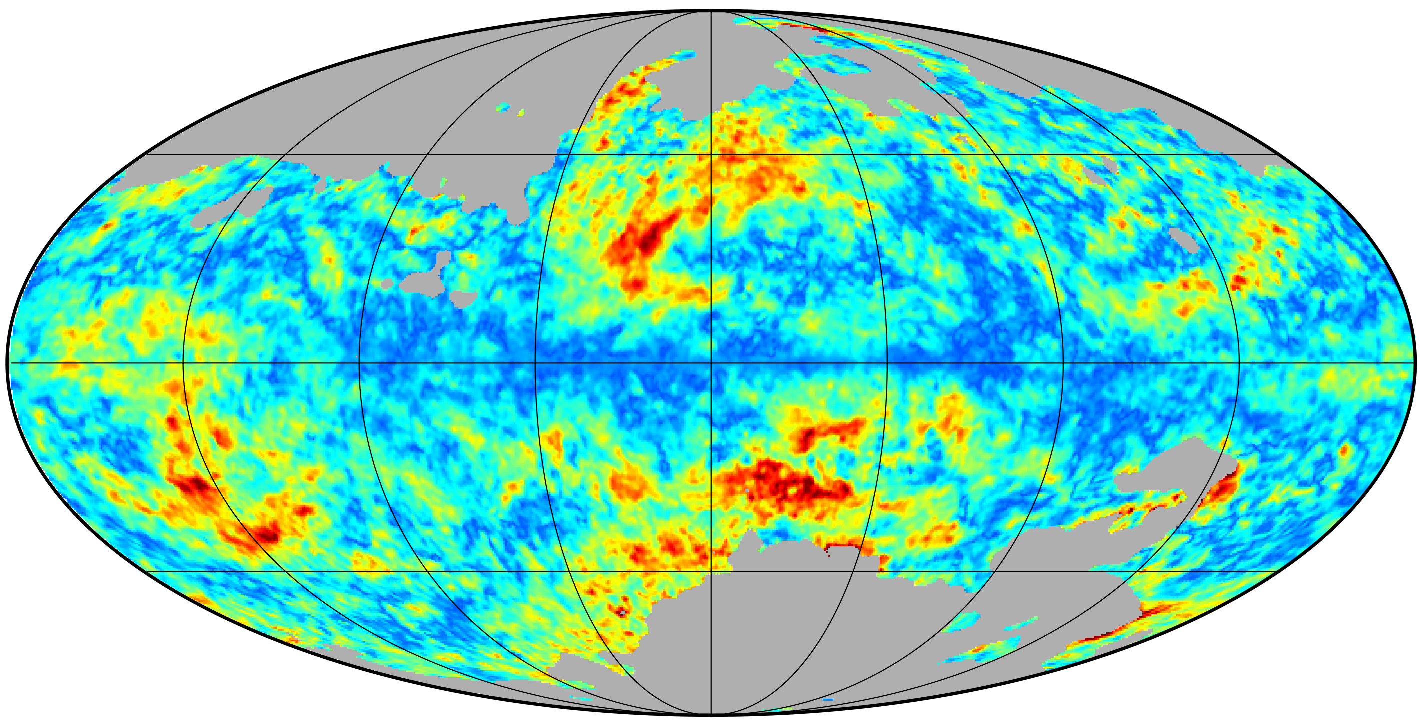

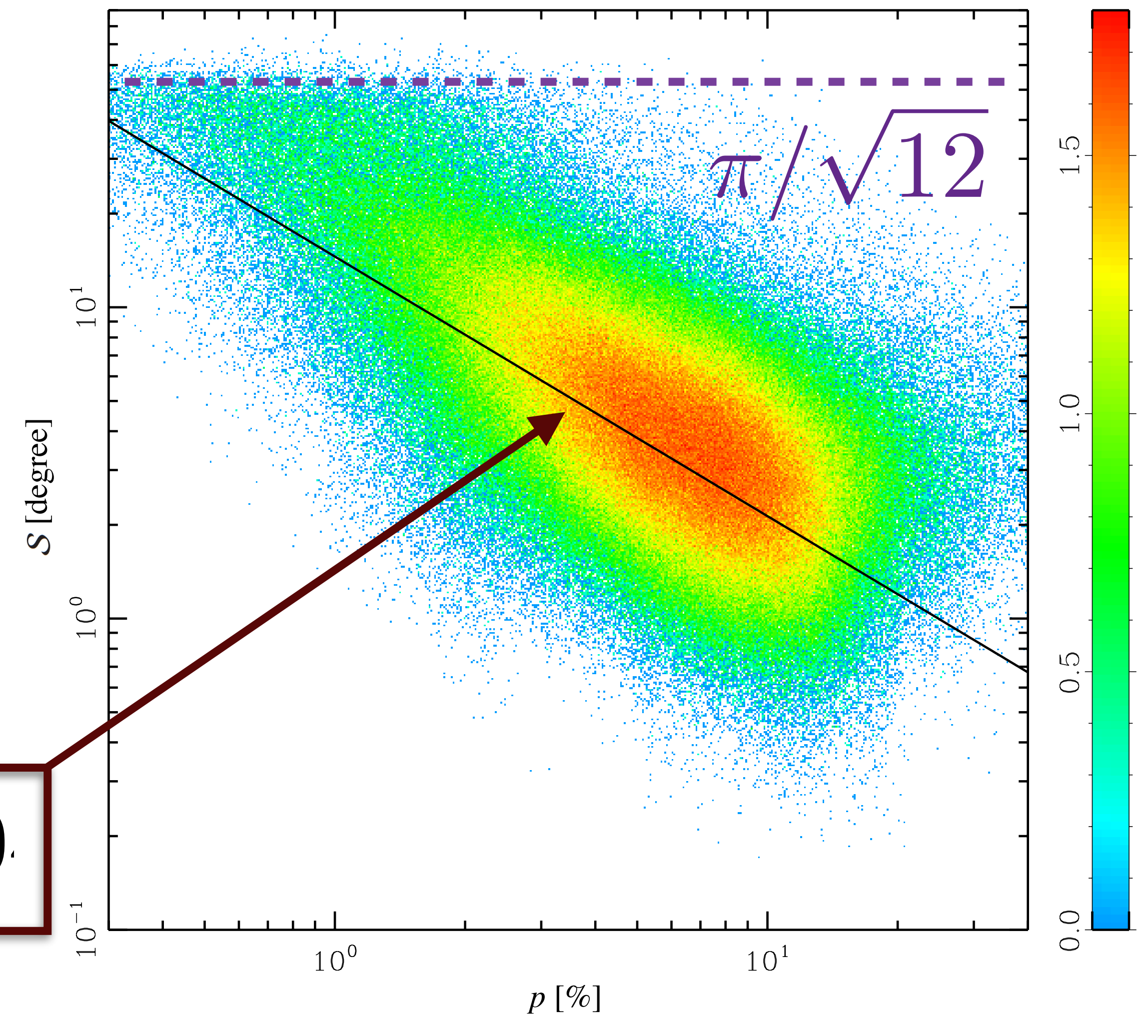

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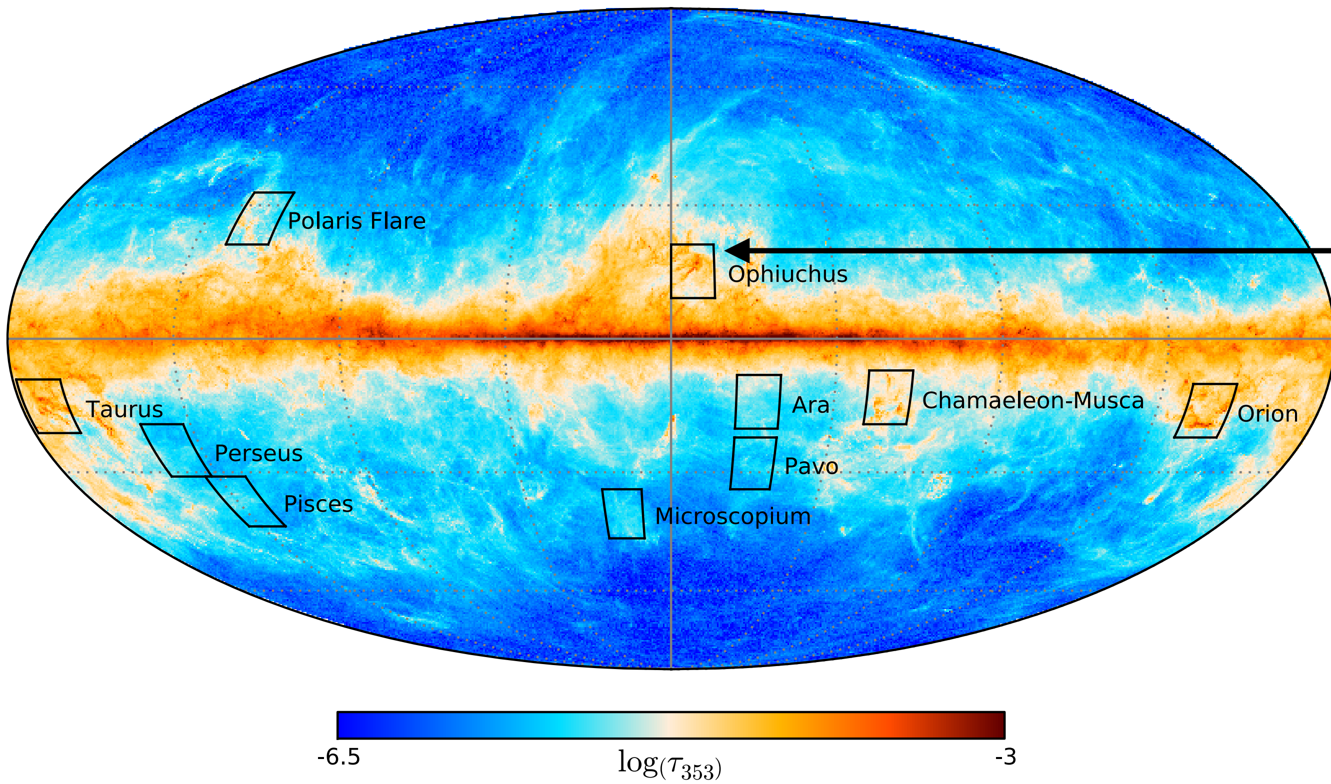
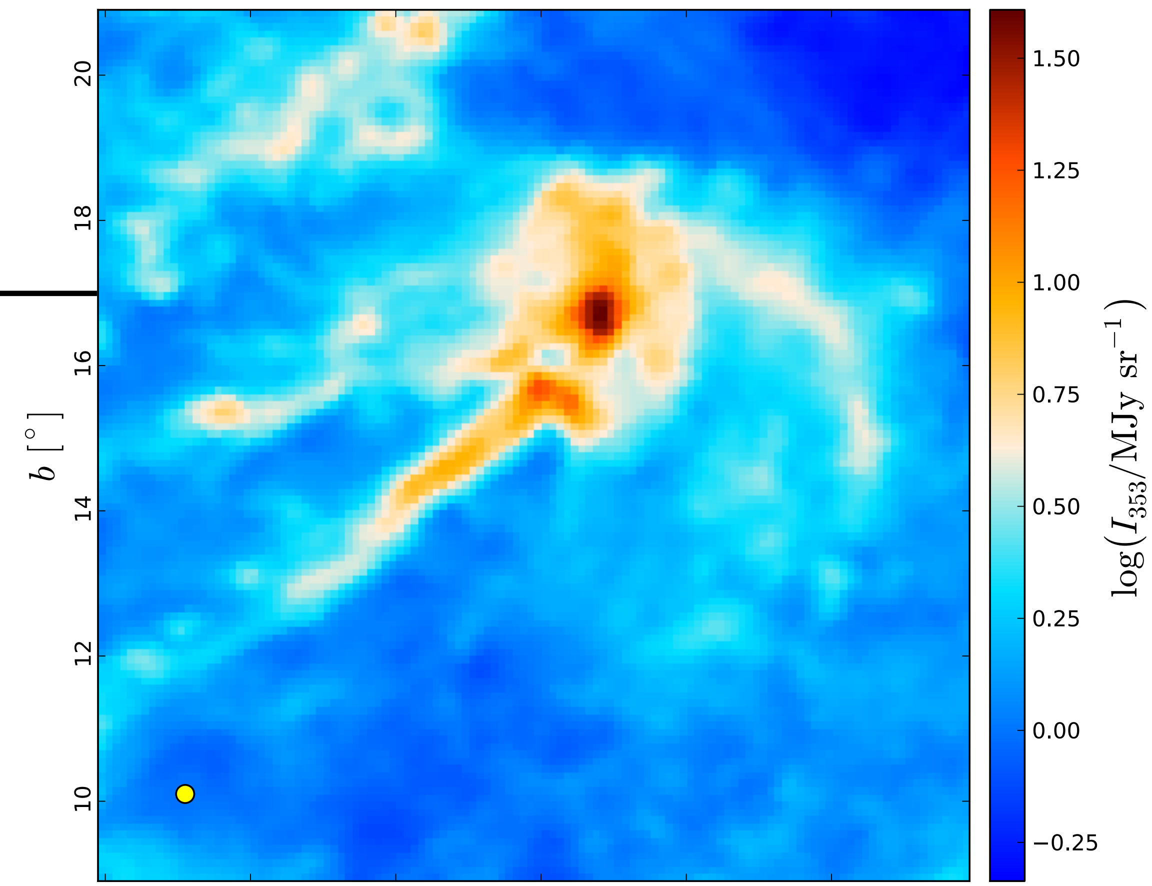
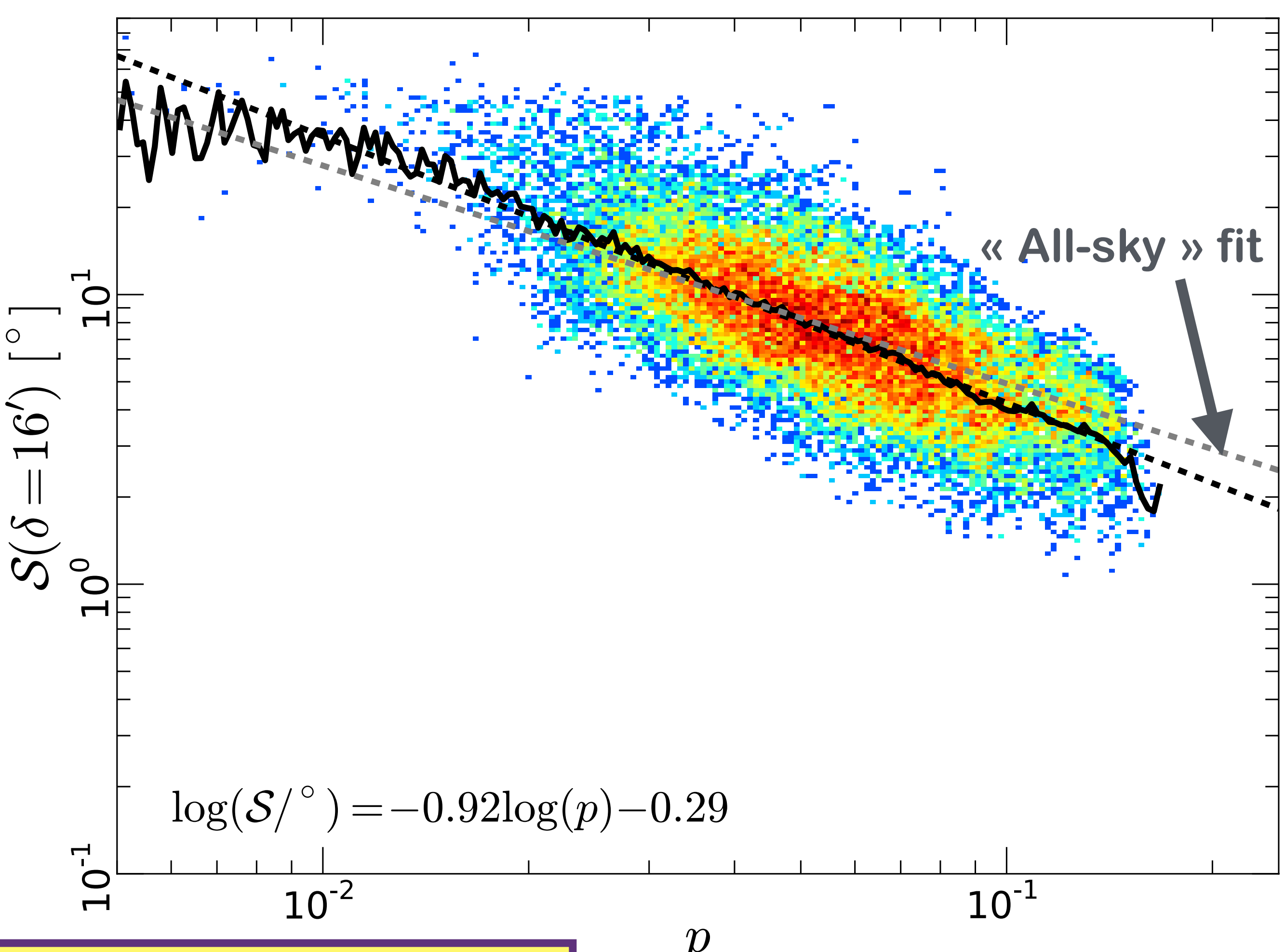
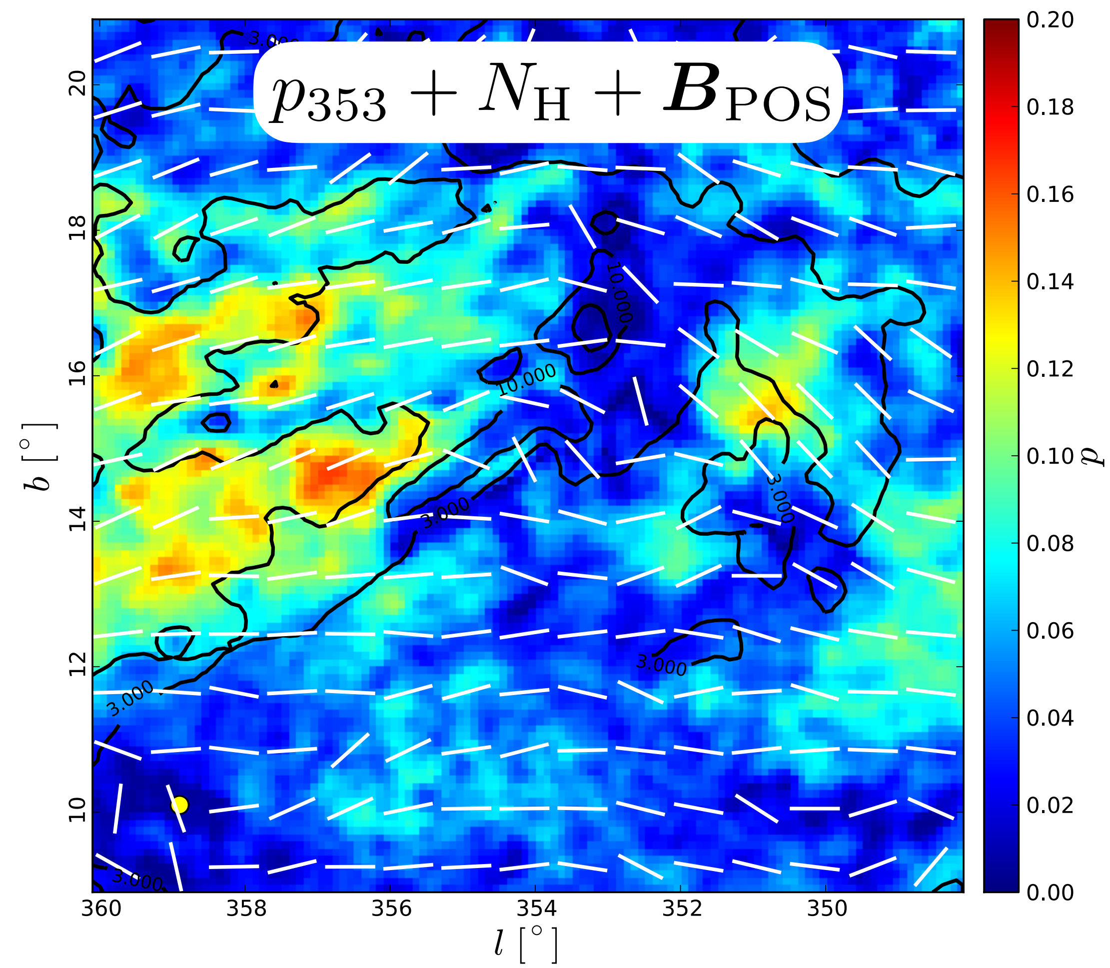
Thermal dust polarization towards molecular clouds









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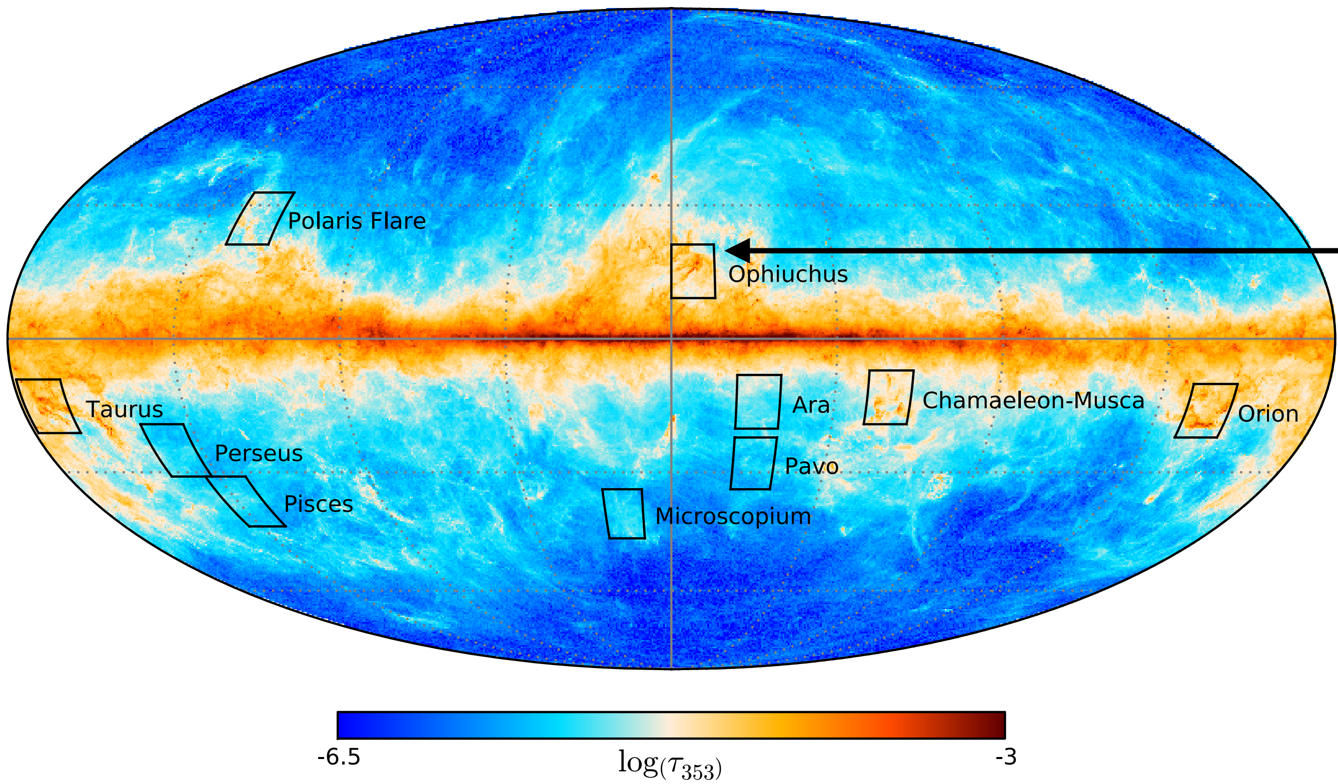
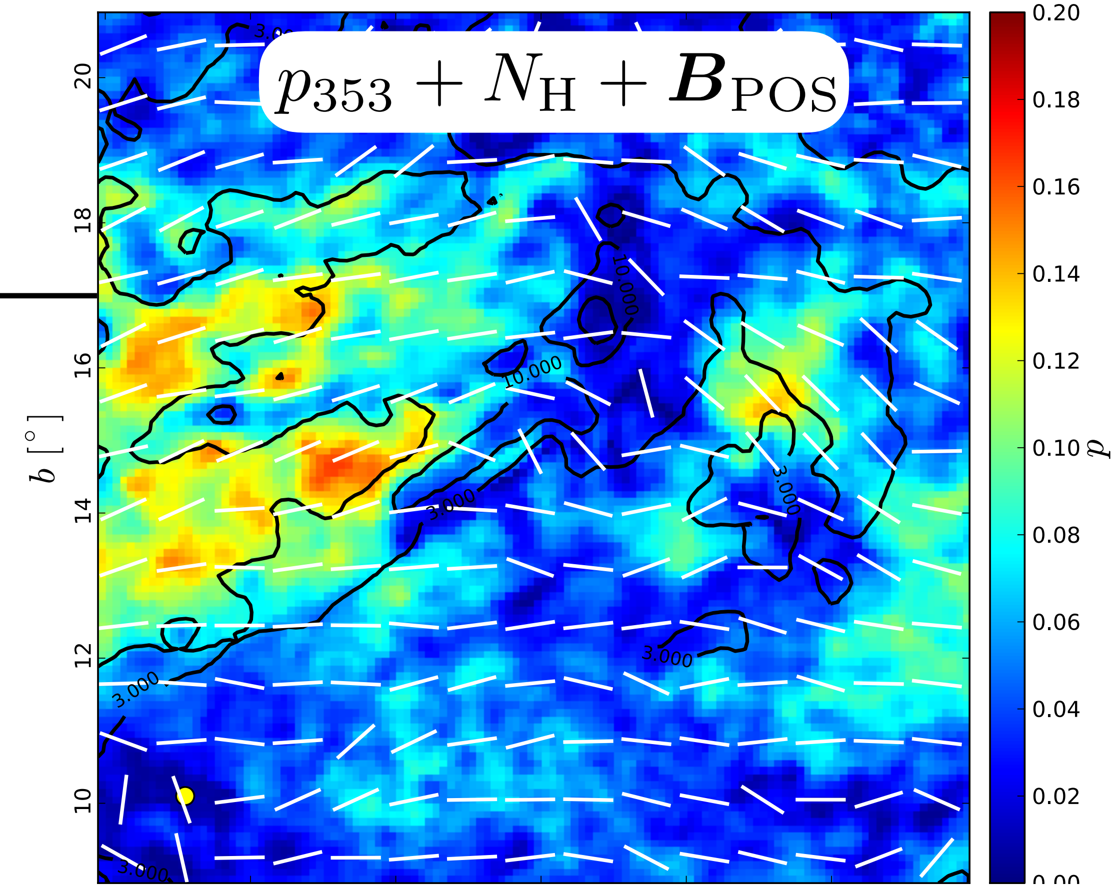
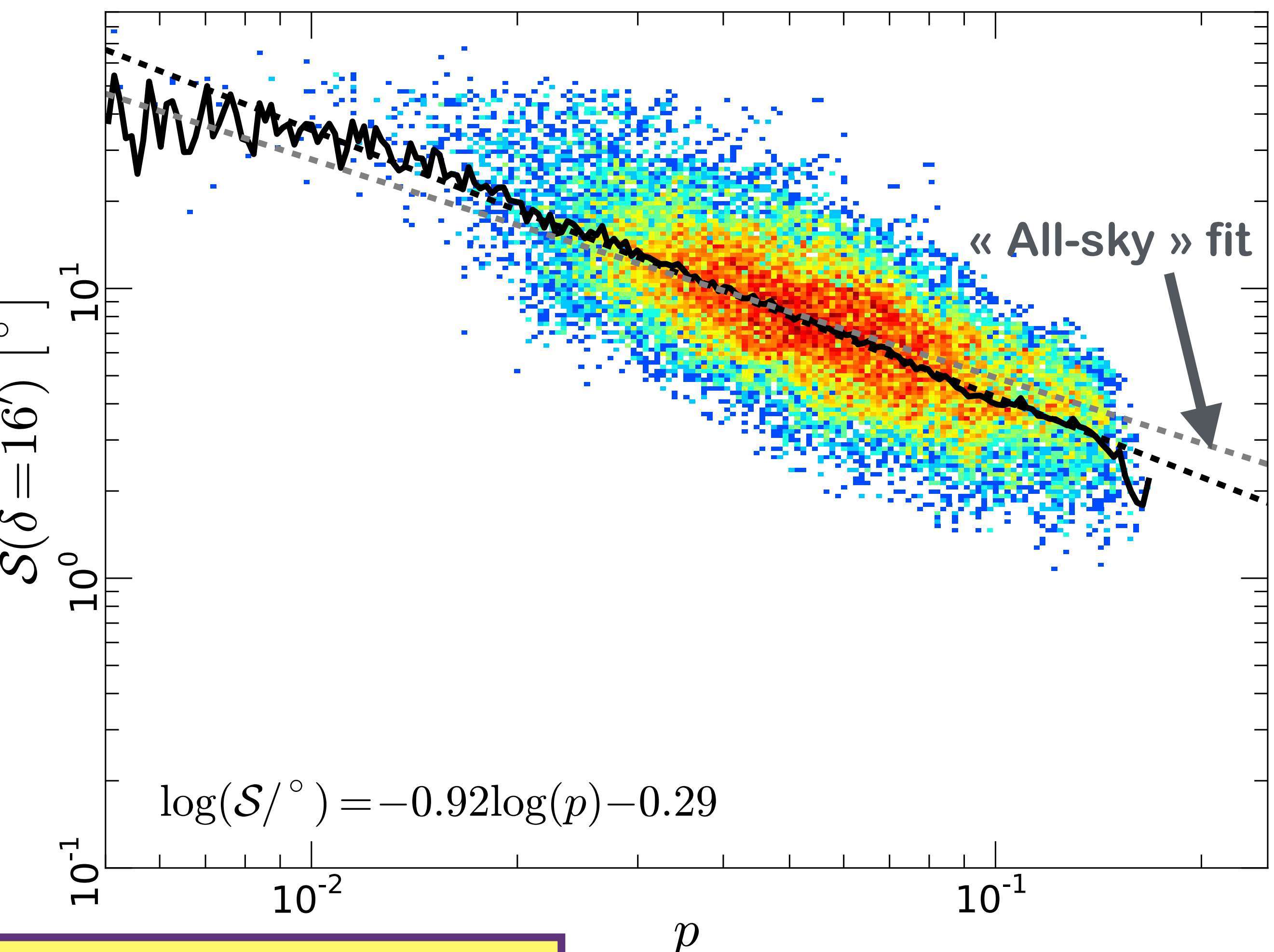
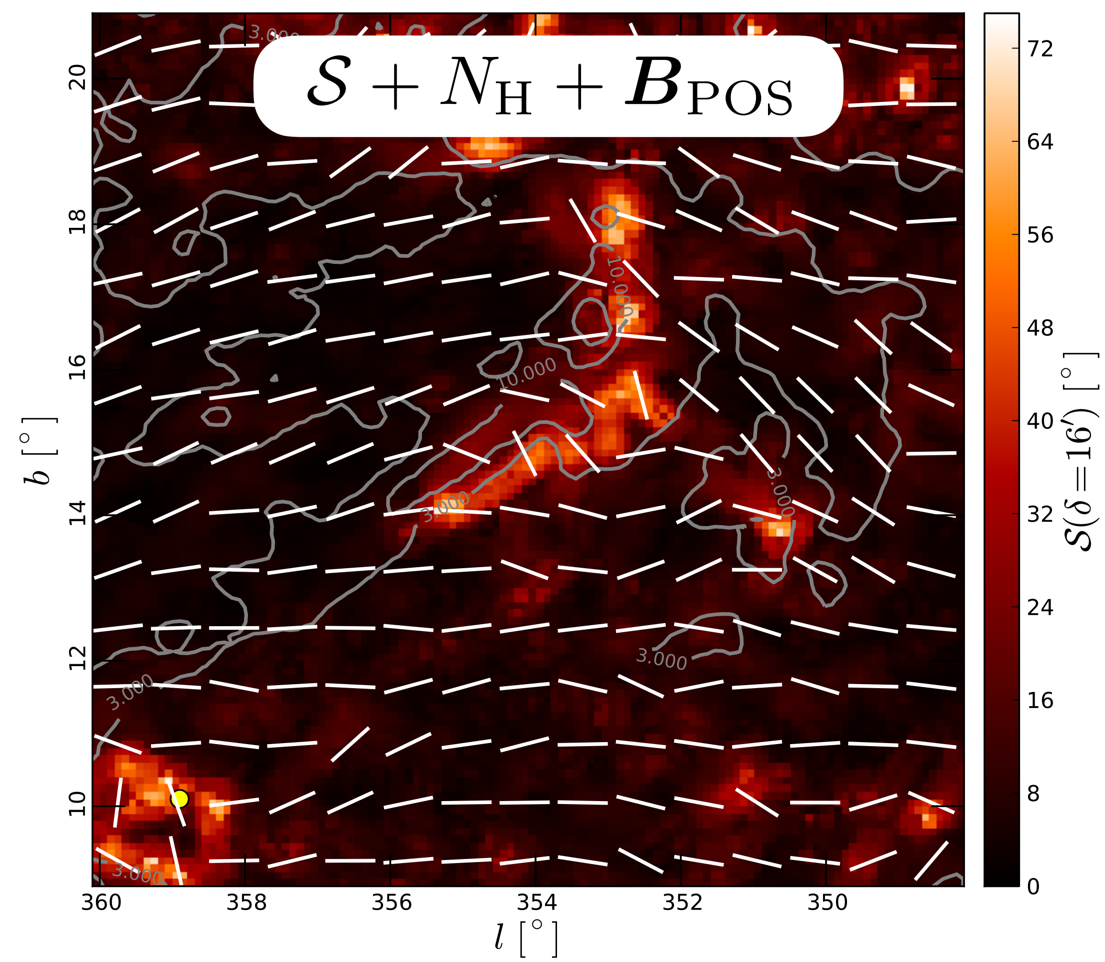
Thermal dust polarization towards molecular clouds









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Comparison with a simulation of anisotropic MHD turbulence

starformat.obspm.fr

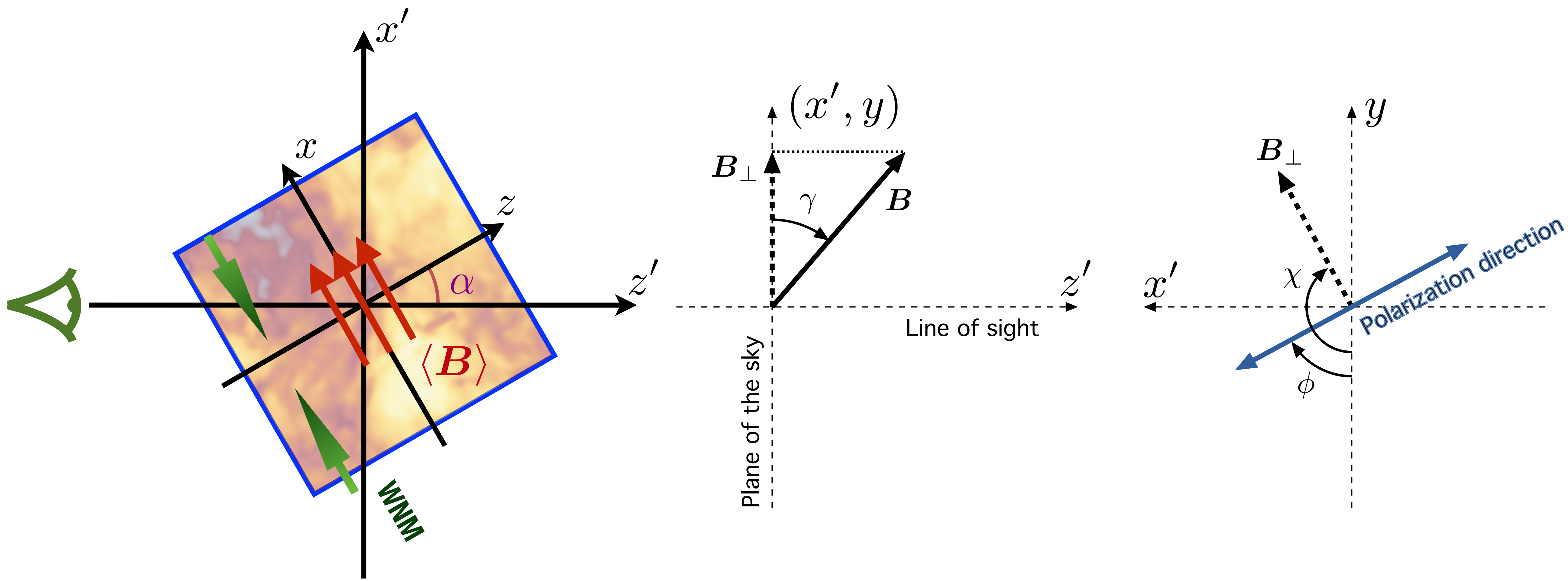
Hennebelle et al. (2008)

- MHD turbulence simulation with self-gravity using RAMSES
- An 18 pc subset of a 50 pc simulation cube
- Converging flows of magnetized warm gas
- Mean magnetic field along the flows
- Rotation of the cube, placed at 100 pc distance
- Uniform dust temperature and intrinsic polarization (20%)
- Simulated Stokes maps at 353 GHz smoothed at 15'

$$I = \int S_\nu e^{-\tau_\nu} \left[1 - p_0 \left(\cos^2\gamma - \frac{2}{3}\right)\right] \mathrm{d}\tau_\nu$$

$$Q = \int p_0 S_\nu e^{-\tau_\nu} \cos(2\phi) \cos^2\gamma \mathrm{d}\tau_\nu$$

$$U = \int p_0 S_\nu e^{-\tau_\nu} \sin(2\phi) \cos^2\gamma \mathrm{d}\tau_\nu$$



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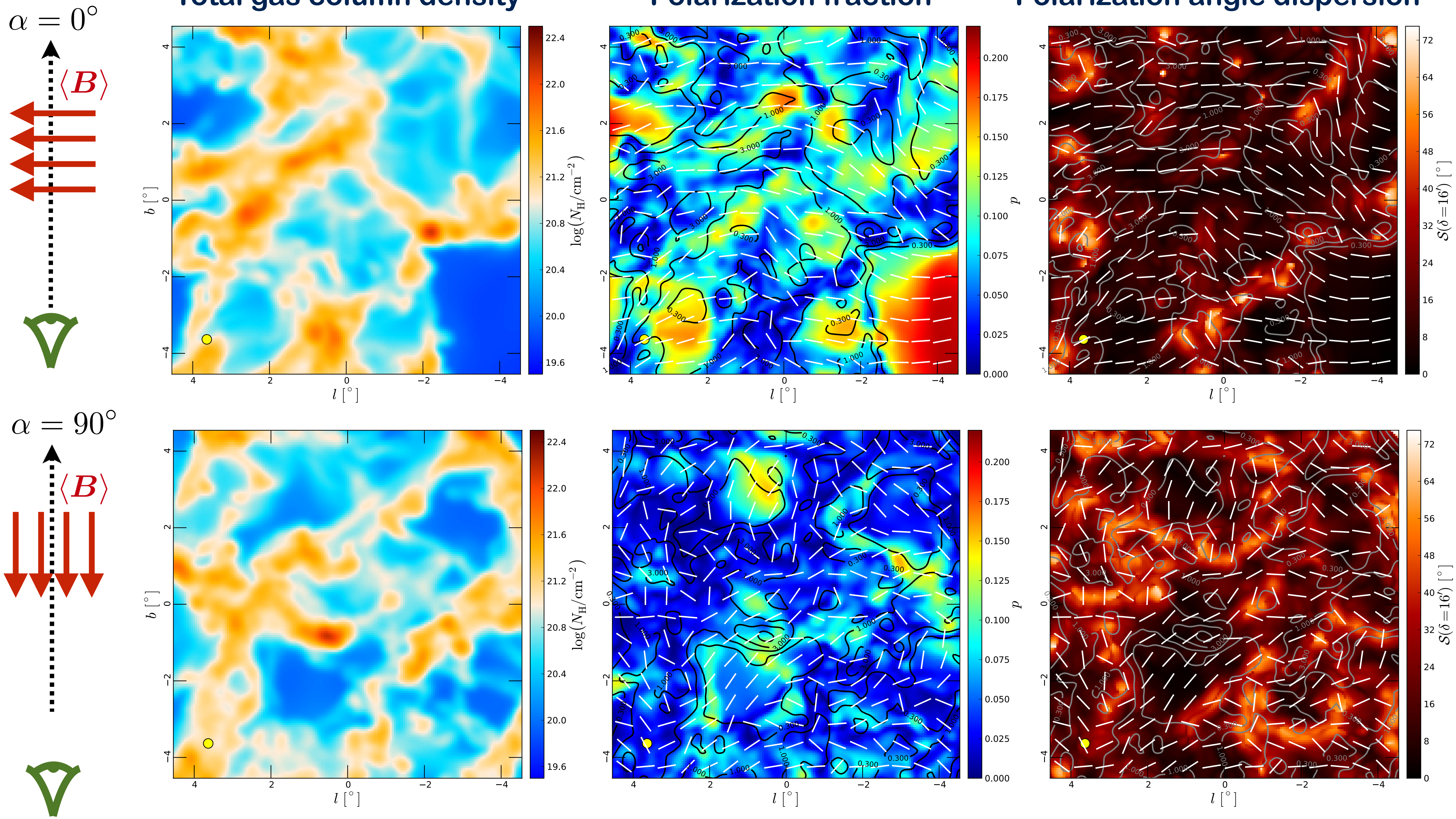
Comparison with a simulation of anisotropic MHD turbulence

Total gas column density | **Polarization fraction** | **Polarization angle dispersion**



- Similar anticorrelations as in the data
- Lower polarization fractions when the mean field is along the LOS

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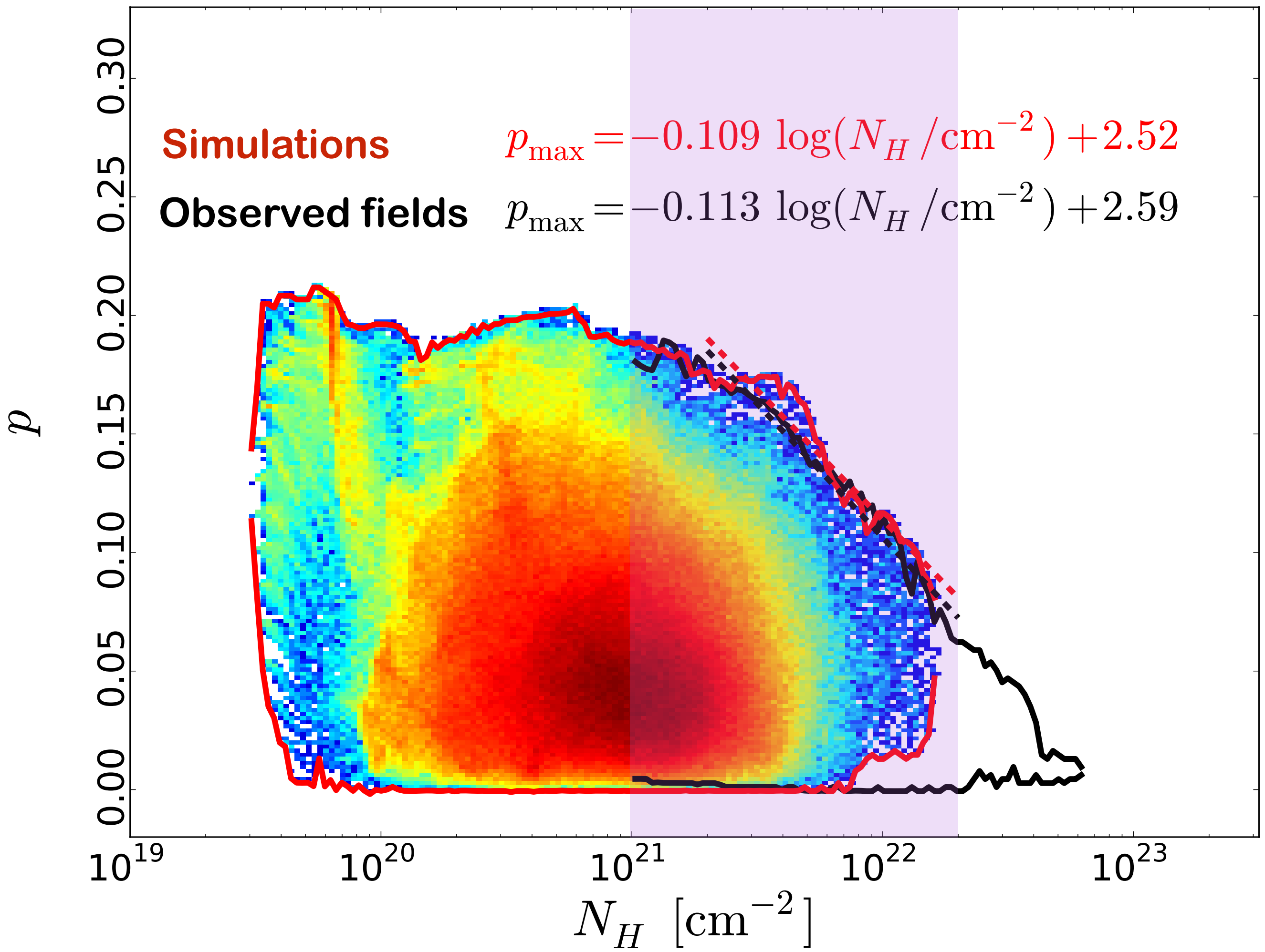
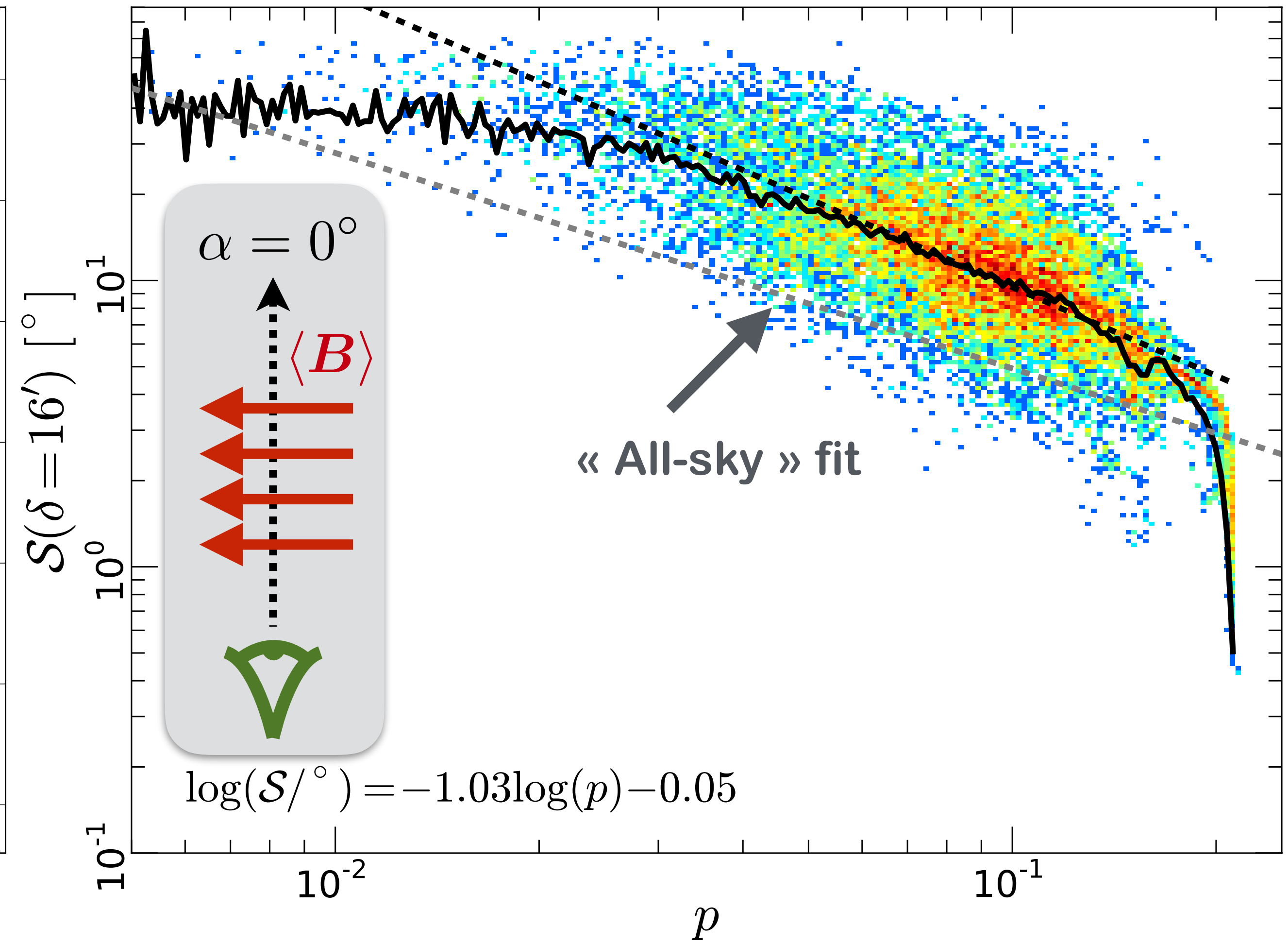
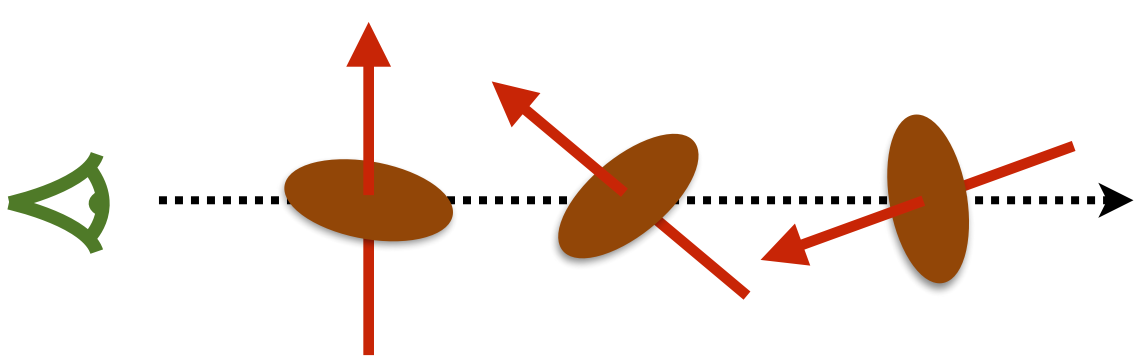
Comparison with a simulation of anisotropic MHD turbulence

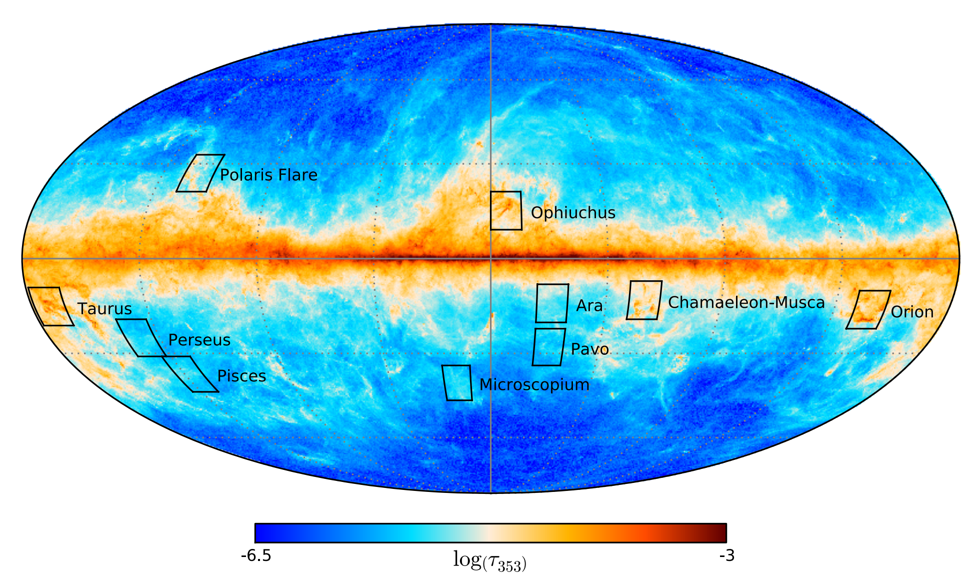




- Simulations reproduce the decrease of the maximum polarization fraction with N_H in that range
- The large scatter at low N_H corresponds to different orientations of the mean magnetic field on the LOS
- The global anti-correlation with the polarization angle dispersion function is reproduced, with a shift

An effect of magnetic field tangling on the line of sight…





Planck Collaboration Int. XX (2015)

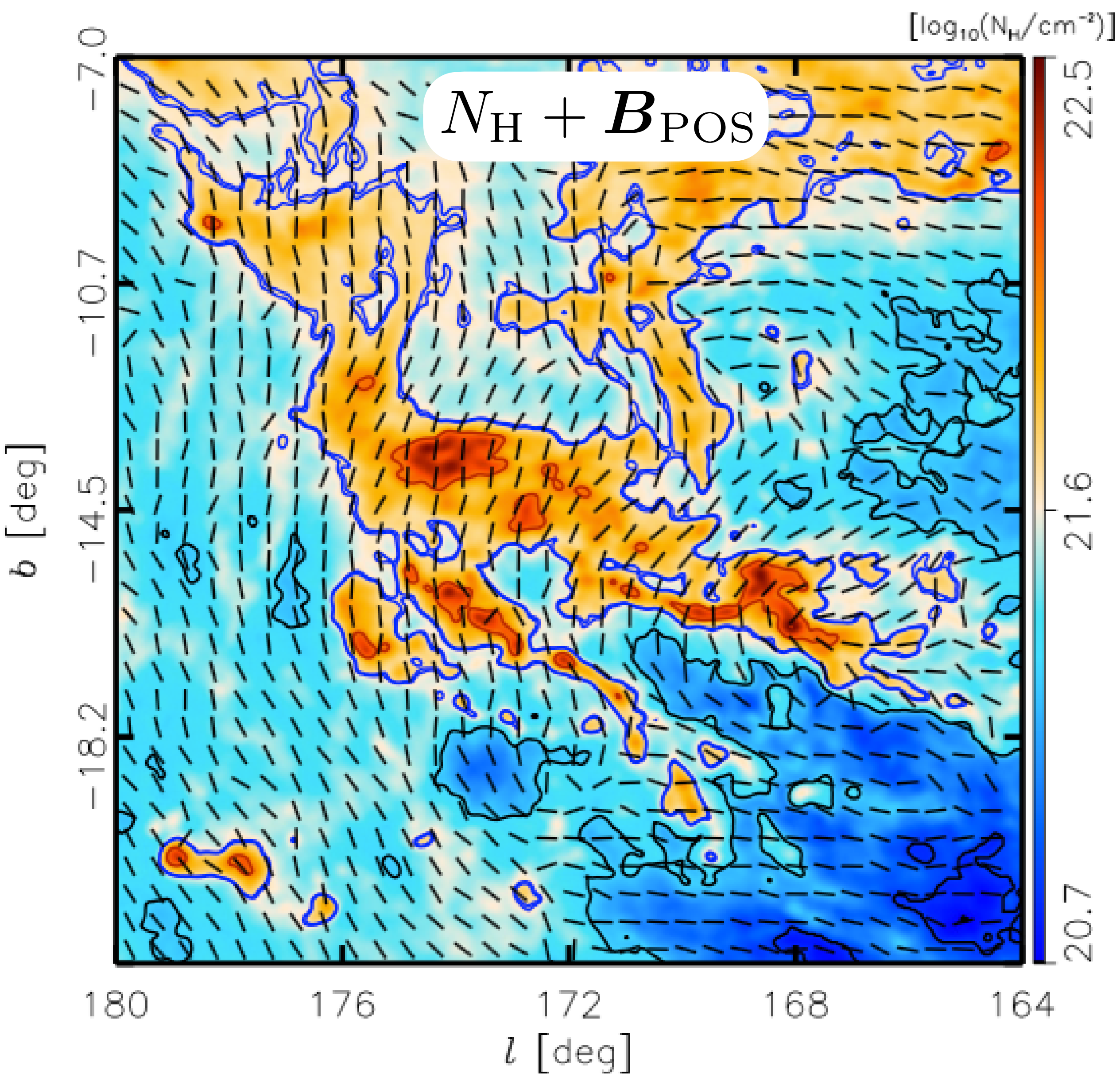
Magnetic field orientation with respect to structures of matter

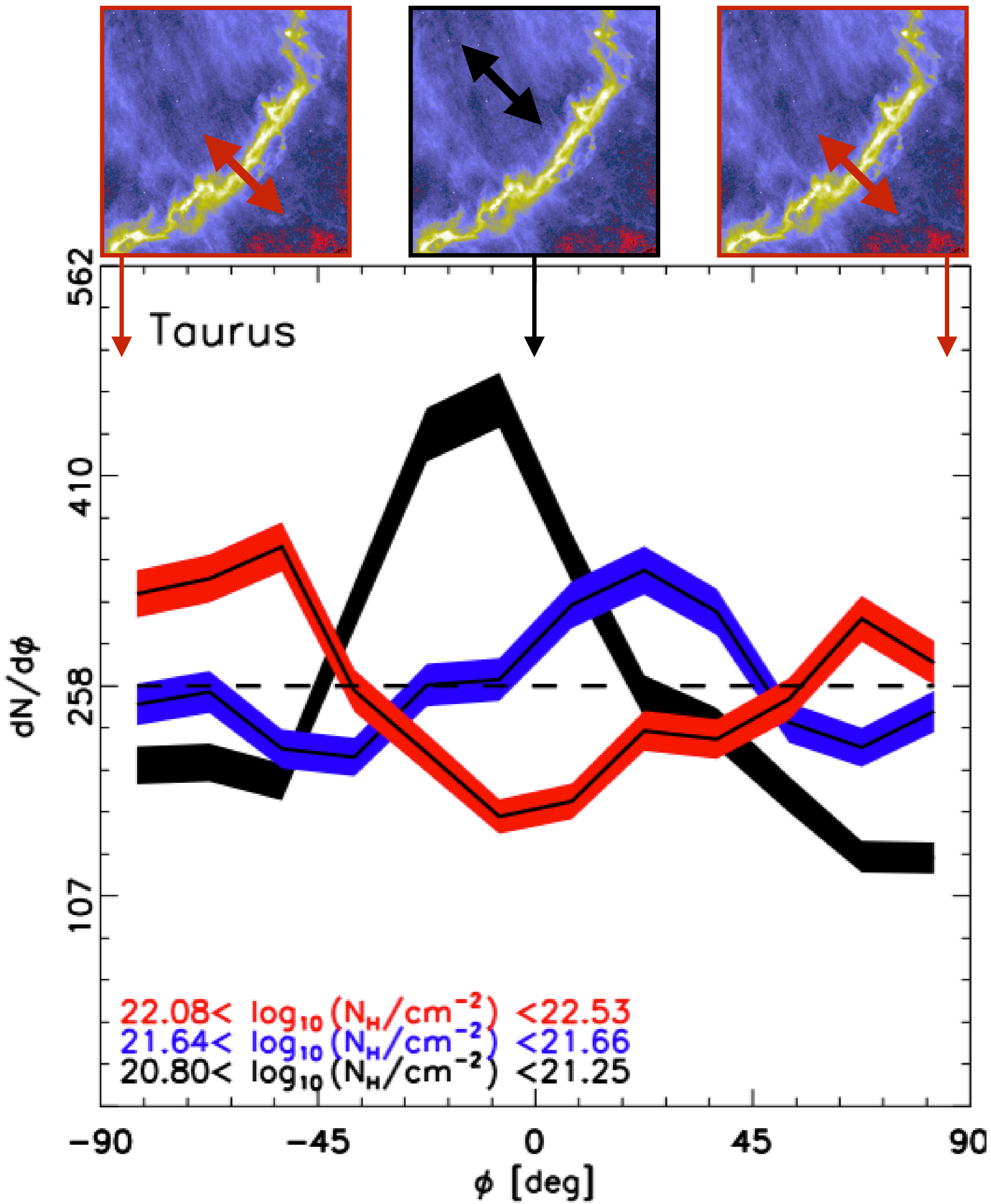
- In nearby molecular clouds, using the Histogram of Relative Orientations (HRO)
- Change of relative orientation as column density increases
- Consistent with sub- and trans-Alfvénic simulations of MHD turbulence (strong magnetic field)
- Estimates of B from the Davis-Chandrasekhar-Fermi method

Soler et al. (2013)

Chandrasekhar & Fermi (1953), Hildebrand et al. (2009)

$$\boldsymbol{B}_{\mathrm{POS}} \sim 10 - 50\,\mu\mathrm{G}$$



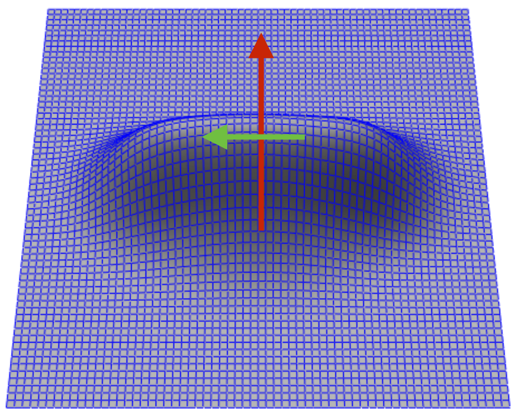


Planck Collaboration Int. XXXV (2016)

Magnetic field orientation with respect to structures of matter

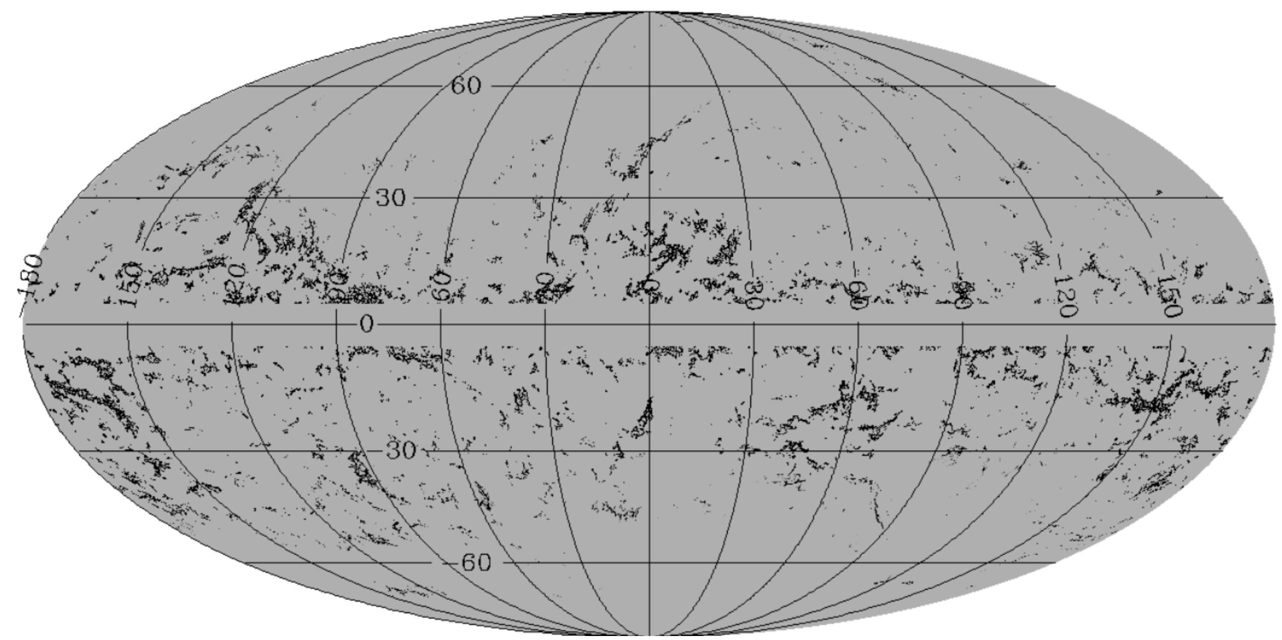
- At intermediate and high Galactic latitudes, using the eigenvalues and eigenvectors of the Hessian
- Relative angle between filaments and magnetic field shows preferred alignment

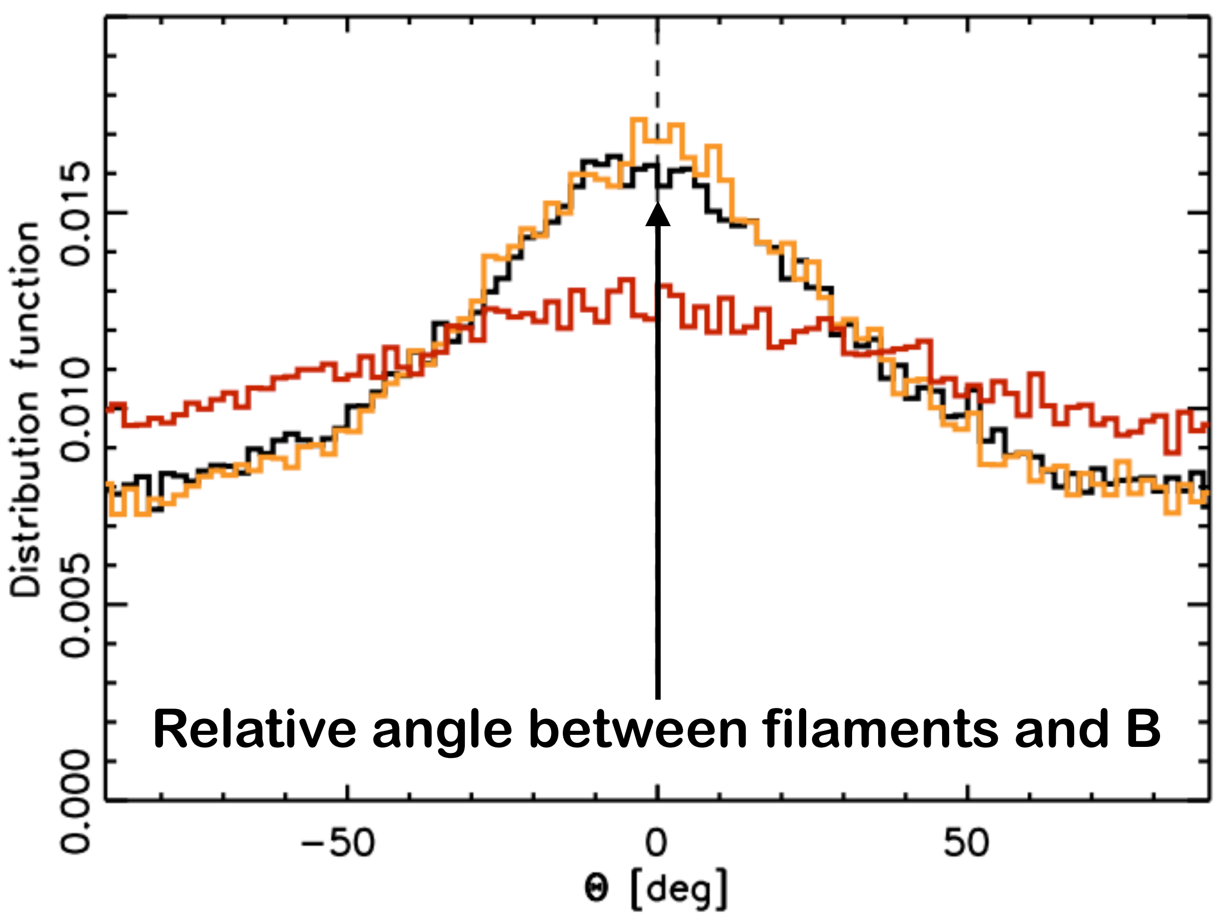
$$\mathbf{H} = \begin{bmatrix} \partial^2_{xx} D_{353} & \partial^2_{xy} D_{353} \\ \partial^2_{xy} D_{353} & \partial^2_{yy} D_{353} \end{bmatrix}$$

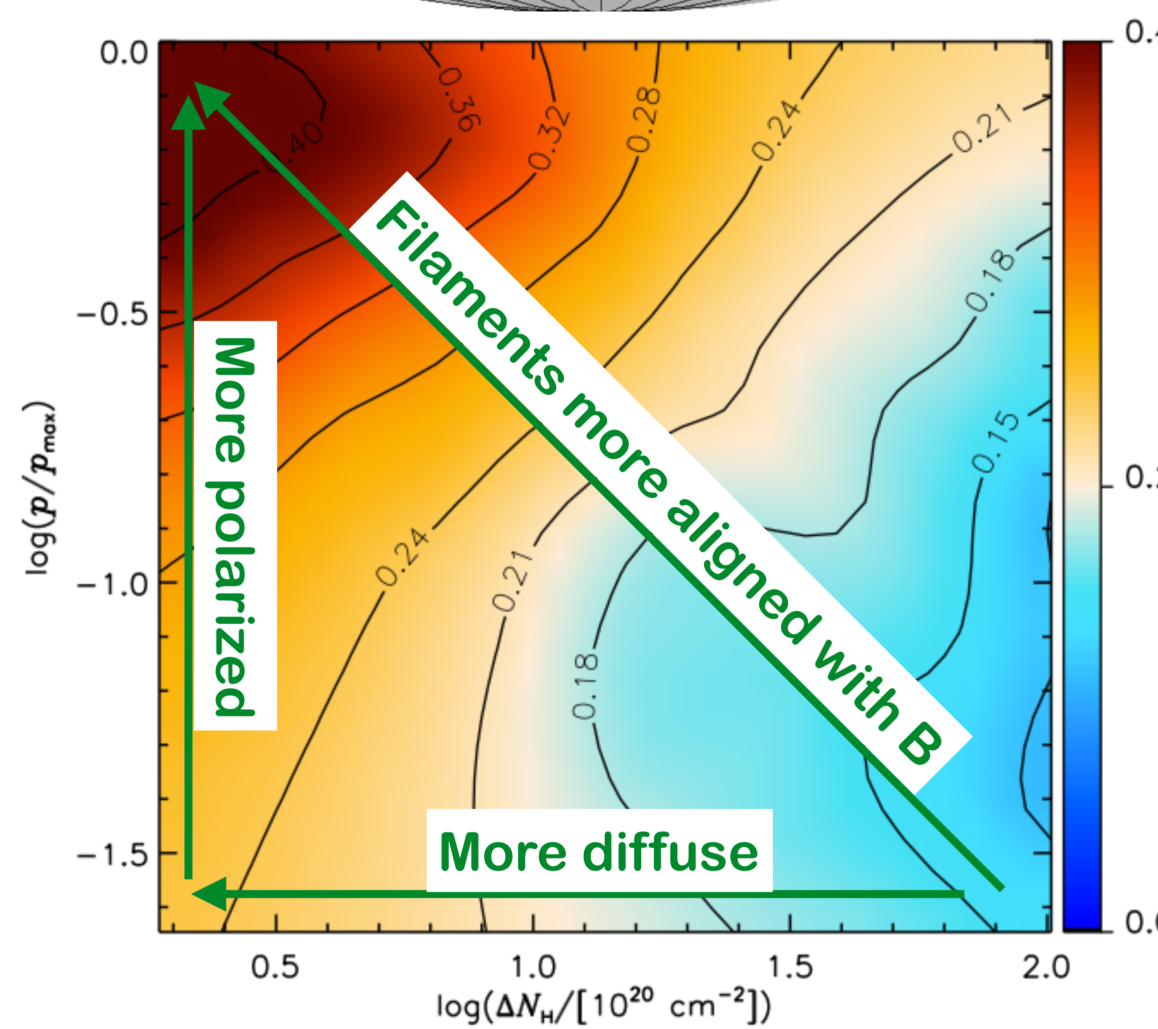


$$\boxed{\langle p \rangle = 12 \pm 1\%}$$

Map of the most negative eigenvalue

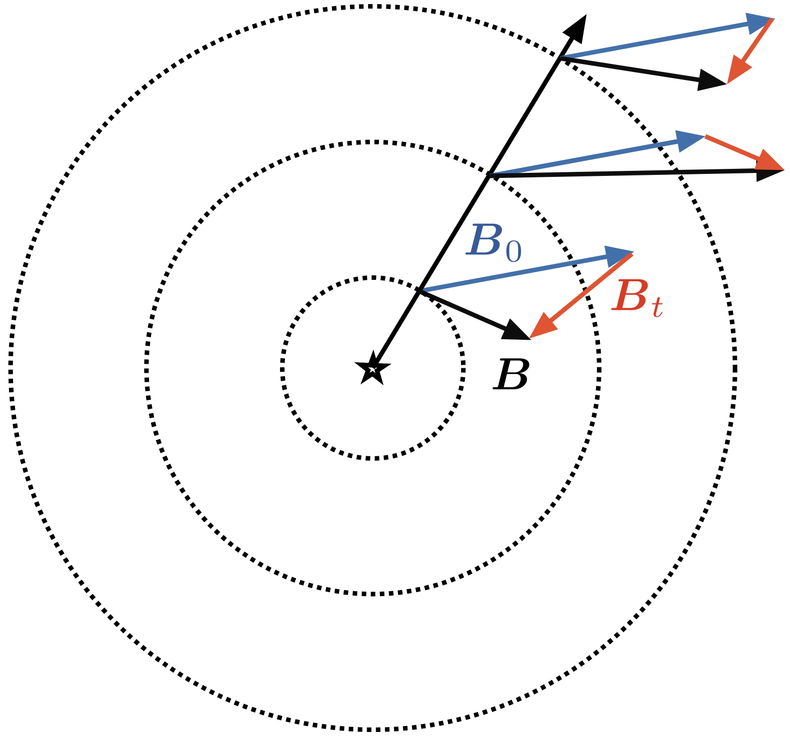






Planck Collaboration Int. XXXII (2016)

A Gaussian model of the polarized sky



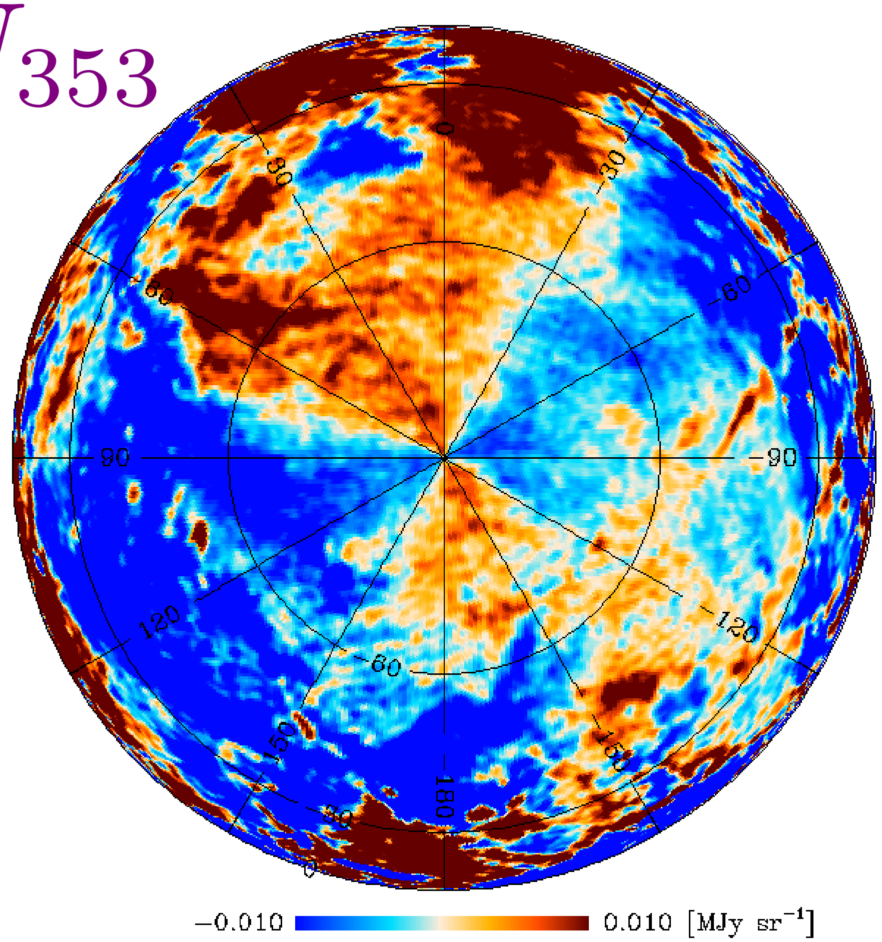
Magnetic field $B = B_0 + B_t$

Uniform field — Turbulent field

- A superposition of variously polarized layers (turbulent cells ?)
- Turbulent field : 3D Gaussian random variable
- Analysis of the Southern Galactic cap

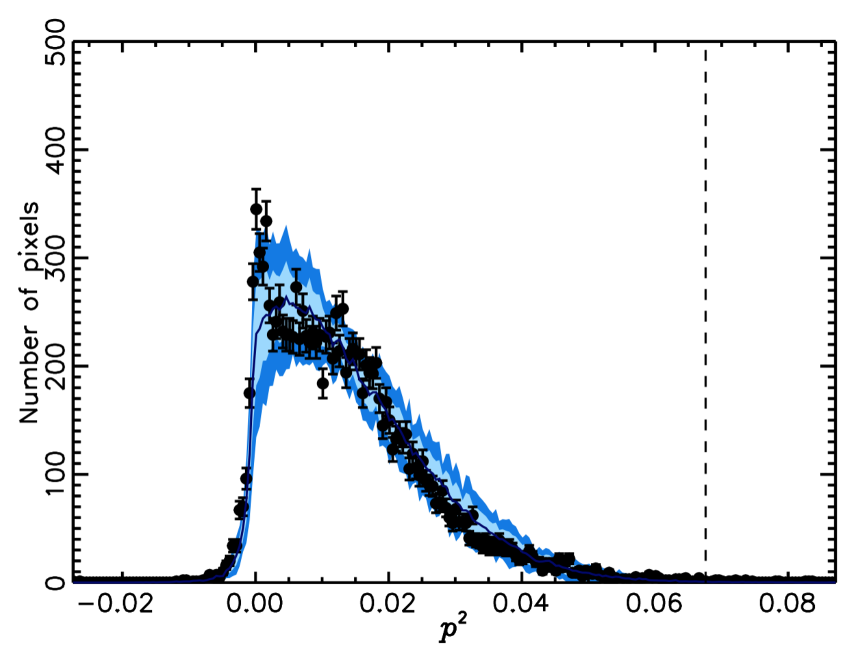
- Spatial power spectrum unconstrained $C_\ell \propto \ell^{\alpha_{\mathrm{M}}}$
- Direction of the large-scale field $(l_0, b_0) = (70 \pm 5°, 24 \pm 5°)$
- Turbulent-to-mean ratio $f_{\mathrm{M}} = 0.9 \pm 0.1$
- Number of layers $N = 7 \pm 2$
- Intrinsic polarization fraction $p_0 = 26 \pm 3\%$

U_{353}

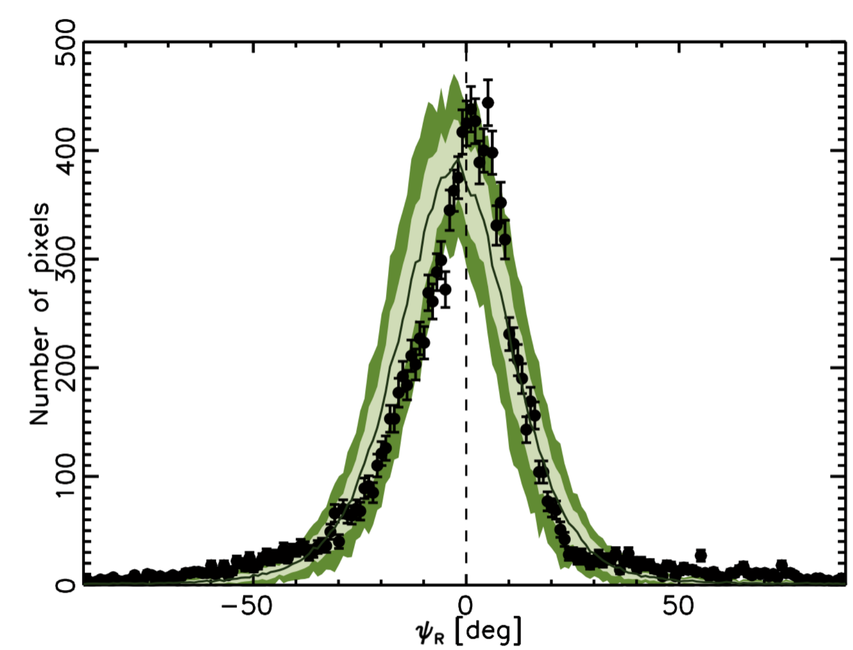


Planck Collaboration Int. XXXII, XLIV (2016)

Observations (black dots) vs. Simulations (colored regions)



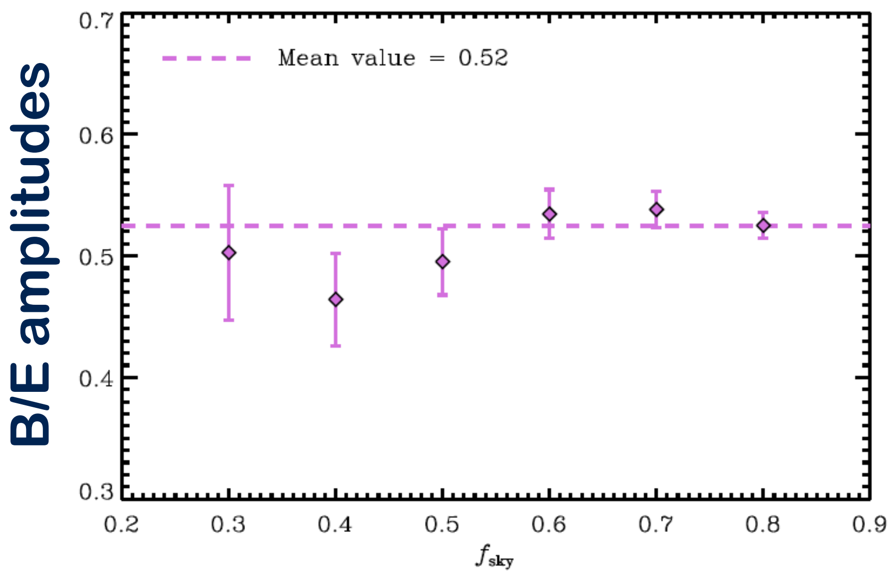
Polarization fraction

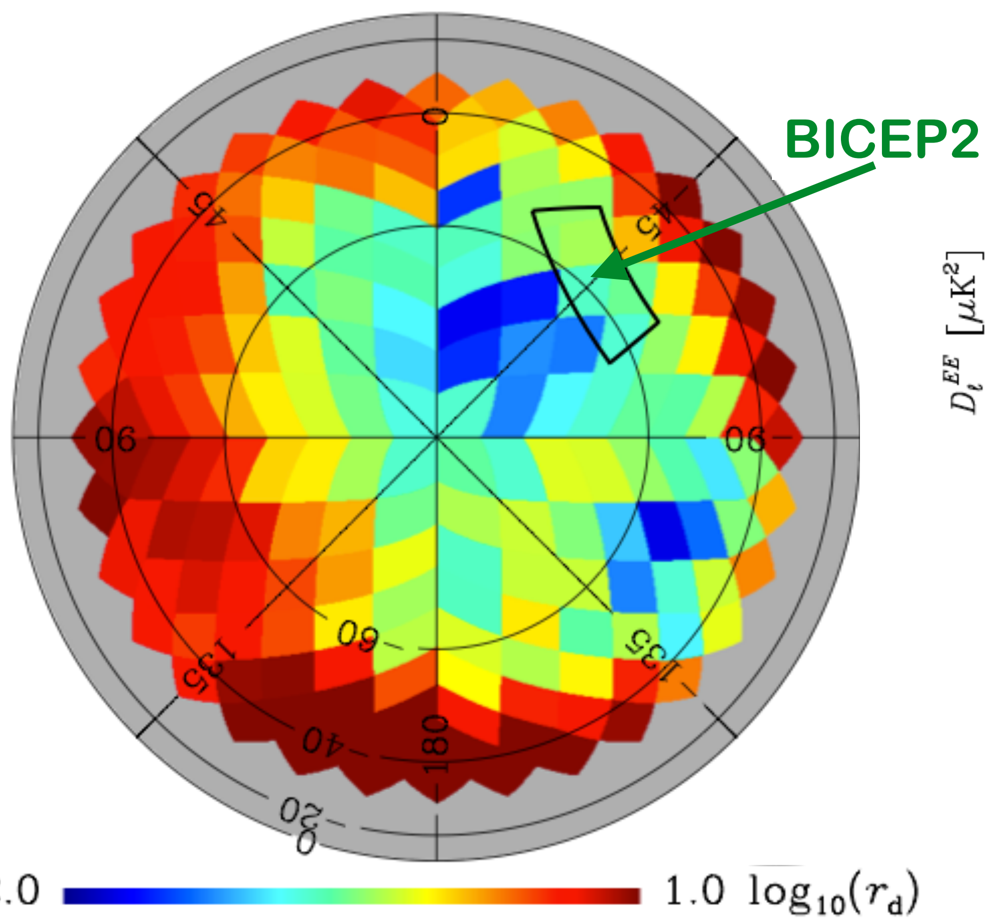


Polarization angle relative to the large-scale field

The angular power spectrum of polarized thermal dust emission

- E and B thermal dust emission angular power spectra outside the Galactic plane well fit by power laws
- Amplitudes vary approximately as the square of average dust brightness in the selected region
- Asymmetry in the E and B modes : twice as much power in E modes
- B mode power attributable to dust in the BICEP2 field compatible with reported detection





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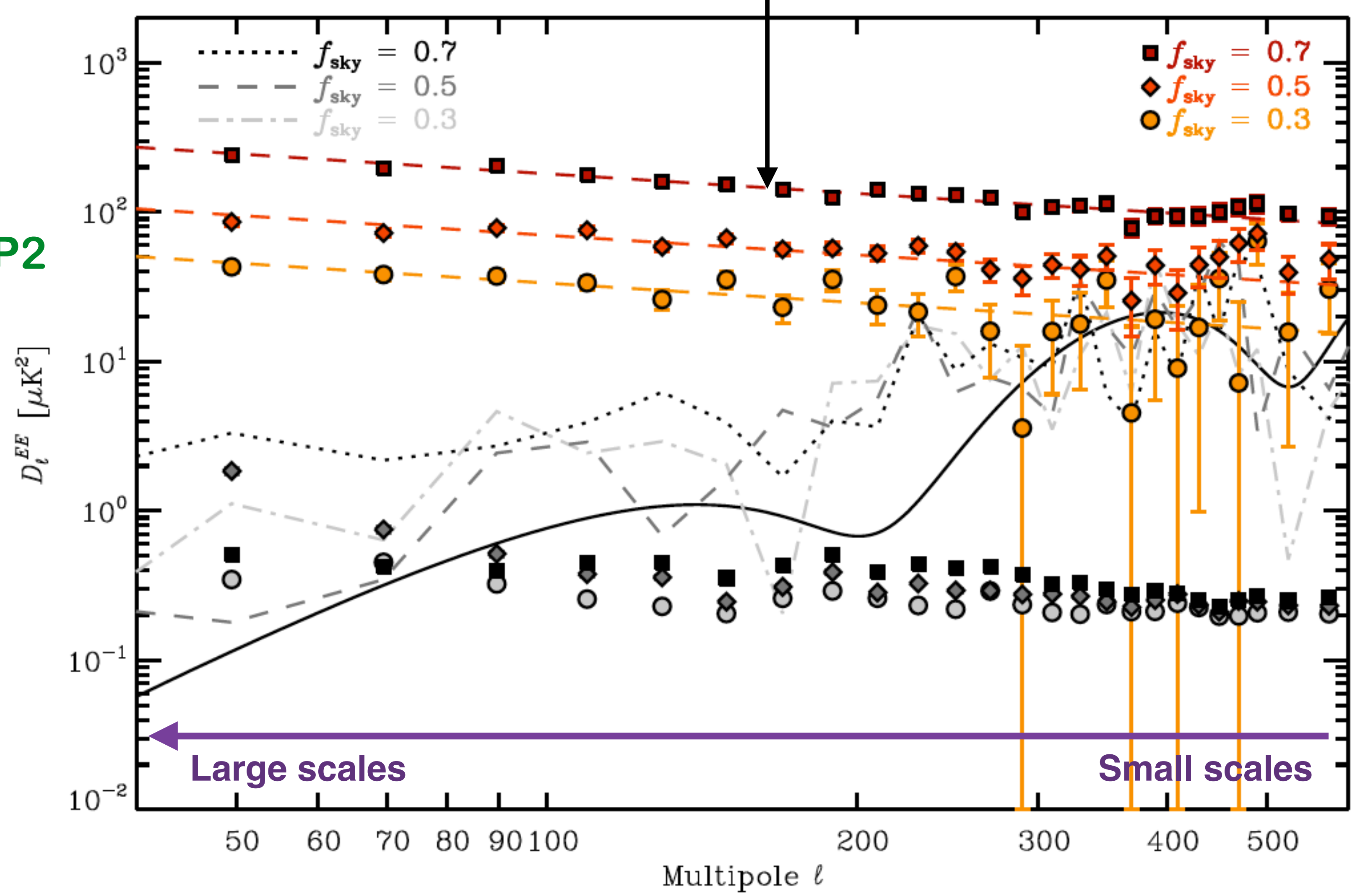
BICEP2 Collaboration (2014) **BICEP2 and Planck Collaborations (2015)**

$$\mathcal{D}_\ell = \frac{\ell(\ell+1)}{2\pi} C_\ell$$



$C_\ell^{EE} \propto \ell^{\alpha_{EE}}$ $C_\ell^{BB} \propto \ell^{\alpha_{BB}}$

$$\boxed{\alpha_{EE,BB} = -2.42 \pm 0.02}$$

Modelling polarized thermal dust emission with fBm fields

- Dust density and magnetic field modelled by 3D fields with realistic spatial correlations
- 9-parameter model (including spectral indices, fluctuation levels, angle of the mean field and depth on the LOS)
- Simulated polarization maps characterized by PDFs, power spectra, and correlations
- Monte-Carlo Markov Chain exploration of parameter likelihood given input polarization maps

Model parameters

Parameter	Prior [a]	Definition
β_B	$[1, 4]$	Spectral index of the 3D turbulent magnetic field
β_n	$[1, 5]$	Spectral index of the 3D dust density field
$\log_{10} y_n$	$[-1, 1]$	Log of the RMS-to-mean ratio of dust density
$\log_{10} y_B^{\mathrm{POS}}$	$[-1, 1]$	Log of the ratio of the turbulent magnetic field RMS to the mean magnetic field in the POS
χ_0	$[-90°, 90°]$	Position angle of the mean magnetic field in the POS
$\log_{10}(d/1\,\mathrm{pc})$	$[-0.3, 1.5]$ [b]	Depth of the simulated cube
$\log_{10}\left(\langle n_{\mathrm{H}}\rangle/1\,\mathrm{cm}^{-3}\right)$	$[1, 2.7]$ [c]	Mean dust density
T_{d}	$[5\,\mathrm{K}, 200\,\mathrm{K}]$	Dust temperature
p_0	$[0.01, 0.5]$	Intrinsic polarisation fraction parameter

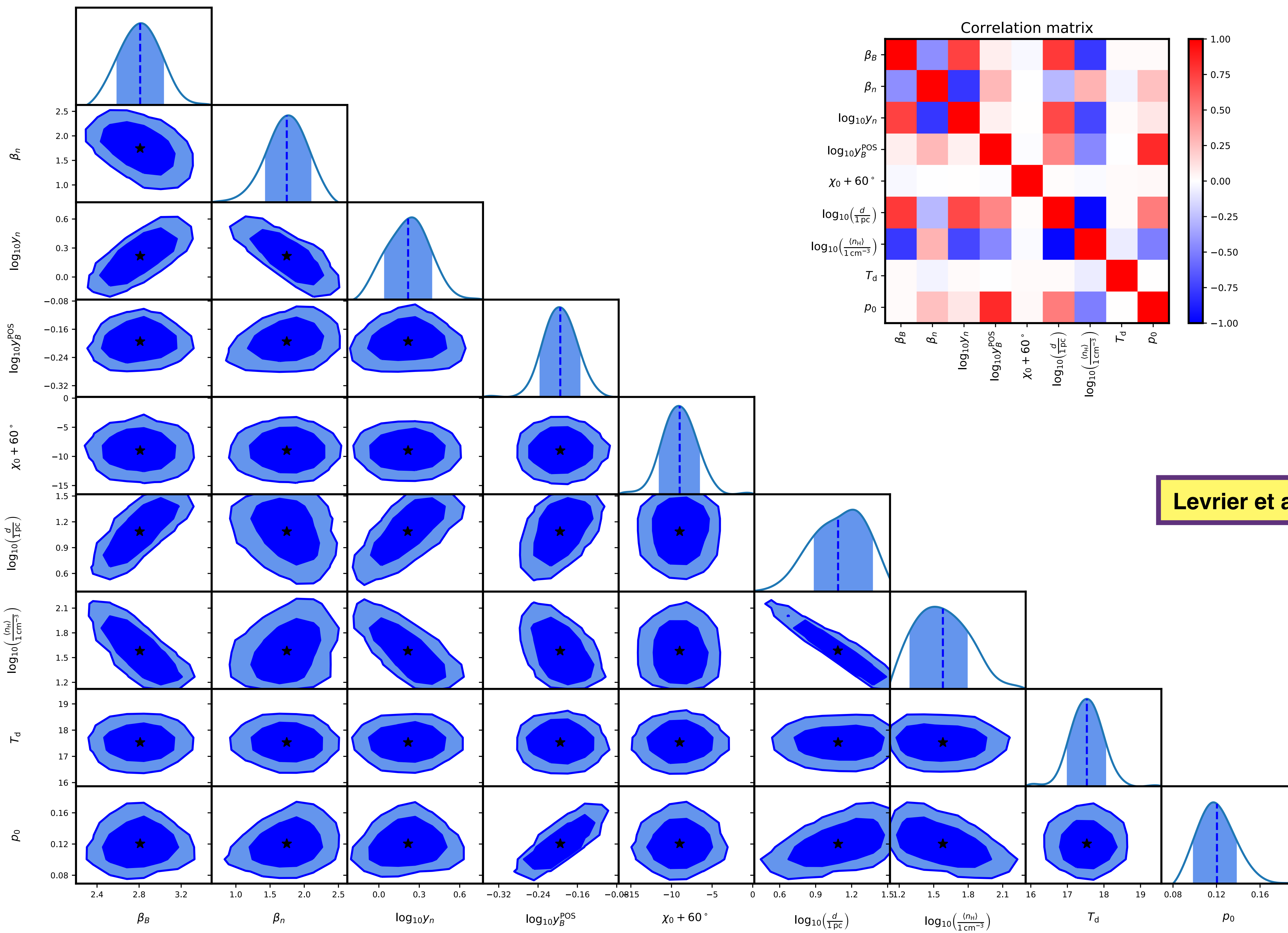
Observables

Type	From
Mean values	τ_{353}, T_{obs}
Distribution function	I_{m}, Q_{m}, U_{m}, p_{MAS}, ψ, $\mathcal{S}$, $\tau_{353}/\langle\tau_{353}\rangle$
Power spectrum	I_{m}, Q_{m}, U_{m}
Correlation	$\{\mathcal{S}, p_{\mathrm{MAS}}\}$

Levrier et al. (submitted)

MCMC fitting on the Polaris Flare Planck polarization maps

Parameters	β_B	β_n	$\log_{10} y_n$	$\log_{10} y_B^{\mathrm{POS}}$	χ_0 [°]	$\log_{10}\left(\frac{d}{1\,\mathrm{pc}}\right)$	$\log_{10}\left(\frac{\langle n_{\mathrm{H}}\rangle}{1\,\mathrm{cm}^{-3}}\right)$	T_{d} [K]	p_0	$\langle\chi^2_{\mathrm{best}}\rangle$
Best fit values	$2.8^{+0.2}_{-0.2}$	$1.7^{+0.4}_{-0.3}$	$0.2^{+0.2}_{-0.2}$	$-0.19^{+0.04}_{-0.04}$	-69^{+2}_{-3}	$1.1^{+0.3}_{-0.2}$	$1.6^{+0.2}_{-0.3}$	$17.5^{+0.5}_{-0.5}$	$0.12^{+0.02}_{-0.02}$	2.9

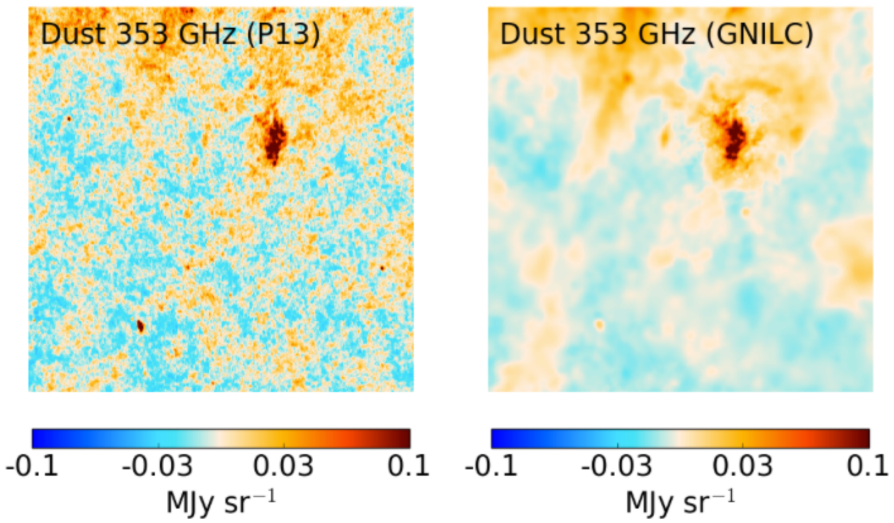


Levrier et al. (submitted)

Perspectives

- Final Planck data release by the end of the year
- Two legacy papers on full-sky dust polarization
- Very-low level of residual systematics
- Using GNILC to separate dust from other components
- ANR program BxB (PI : F. Boulanger)
  - ✦ Modelling of the large-scale field in the local bubble
  - ✦ Statistical description of the turbulent, magnetized ISM using tools from texture analysis
  - ✦ Component separation methods in polarization for future CMB missions

GNILC effectively separates dust from CIB, CMB and noise



Planck Collaboration Int. XLVIII (2016)

Wavelet scattering transform (S. Mallat, ENS department of computer science)

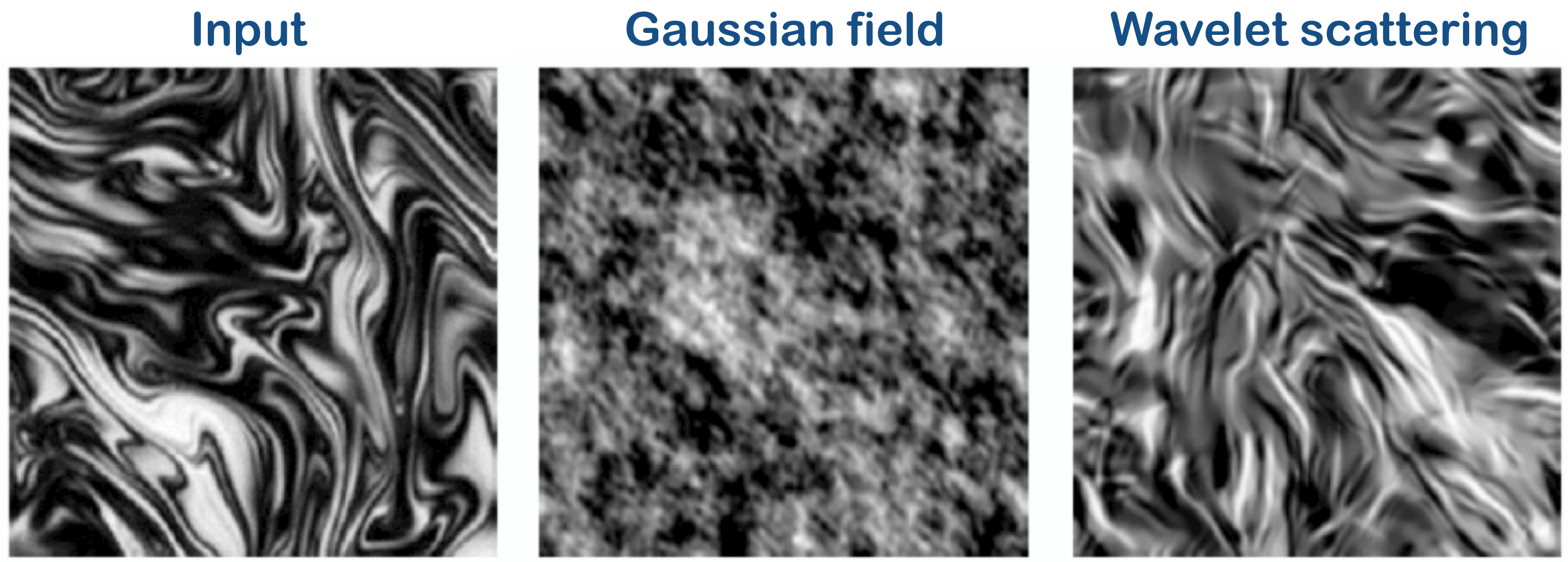


Fig. courtesy S. Mallat